4

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An Experimental Examination of Selected Maneuvers That May Induce On-Road Untripped, Light Vehicle Rollover - Phase I-B of NHTSA's 1997-1998 Vehicle Rollover Research Program

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16. Abstract

The research described in this report is a natural outgrowth of the work that was performed for Phase I-A of the National Highway Traffic Safety Administration's (NHTSA) 1997 - 1998 Light Vehicle Rollover Research program. When originally planned, NHTSA's 1997 - 1998 Light Vehicle Rollover Research program was to consist of the Phase I research which was to develop a set of test maneuvers to be used, and the Phase II research which was to use the Phase I maneuver set to measure the on-road, untripped, maneuver induced rollover propensities of a broad range of vehicles. However, preliminary analysis of the Phase I-A results revealed a number of issues that had to be resolved before the Phase II testing could begin. Therefore, the spring through fall of 1997 testing was renamed the Phase I-A research and additional testing, called the Phase I-B research, was performed during the fall of 1997 and the winter and spring of 1998. During the latter part of Phase I-A, it was decided that a steering controller should be purchased to provide more repeatable steering inputs. While waiting for delivery of the steering controller, several studies were conducted to evaluate driver, outrigger, and fuel level effects on test results.

The objectives of Phase I-B Light Vehicle Rollover Research program were to: develop an understanding of driver variability, outrigger, and fuel level effects on test results; procure and implement testing with a programmable steering controller; and make a final determination of the maneuvers to be selected for use in Phase II of the Light Vehicle Rollover Research program.

There were several driver effects found, but these are greatly diminished with the use of the steering controller. Based on limited results, the outriggers tend to dampen the response at higher frequencies and increase the response at lower frequencies. These changes appear to be relatively small especially for the normal outrigger case. Fuel level appears to have a negligible effect on test results.

Four Vehicle Characterization and five Untripped Rollover Propensity maneuvers were developed for Phase II Research. The four Vehicle Characterization maneuvers are: Pulse Steer, Sinusoidal Sweep, Slowly Increasing Steer, and Slowly Increasing Speed. The five Untripped Rollover Propensity maneuvers are: J-Turn, J-Turn with Pulse, Fishhook #1, Fishhook #2, and Resonant Steer.

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TABLE OF CONTENTS

TABLE OF CONTENTS (continued)

Section **Page**

TABLE OF CONTENTS (continued)

Section **Page**

TABLE OF CONTENTS (continued)

Section **Page**

LIST OF FIGURES

LIST OF FIGURES (continued)

LIST OF FIGURES (continued)

Figure **Page**

LIST OF FIGURES (continued)

Figure **Page**

LIST OF FIGURES (continued)

Figure **Page**

LIST OF FIGURES (continued)

Figure **Page**

LIST OF FIGURES (continued)

Figure **Page**

LIST OF TABLES

LIST OF TABLES (continued)

Table **Page**

LIST OF TABLES (continued)

Table **Page**

LIST OF TABLES (continued)

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John Hinch from NHTSA Research and Development and Mike Pyne, Gayle Dalrymple, Pat Boyd, and Gary Woodford from NHTSA Safety Performance Standards office contributed to the development of the test procedures used in this study.

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Department of Transportation
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TECHNICAL SUMMARY

Report Title: An Experimental Examination of Selected Maneuvers That May Induce On-Road Untripped, Light Vehicle Rollover - Phase I-B of NHTSA's 1997-1998 Vehicle Rollover Research Program	Date: April 2002
Report Author(s): J. Gavin Howe, W. Riley Garrott, Garrick Forkenbrock	

This report documents the results of the Phase I-B testing for the National Highway Traffic Safety Administration's (NHTSA) 1997-1998 Light Vehicle Dynamics Rollover Research program. When originally planned, this research program was to consist of the Phase I research (to be performed during the spring through fall of 1997) which was to develop a set of test maneuvers to be used, and the Phase II research (to be performed during the summer of 1998) which was to use the Phase I maneuver set to measure the on-road, untripped, maneuver induced rollover propensities of a broad range of vehicles. However, preliminary analysis of the Phase I results revealed a number of issues that had to be resolved before the Phase II testing could begin. Therefore, the spring through fall of 1997 testing was renamed the Phase I-A research and additional testing, called the Phase I-B research, was performed during the fall of 1997 and the winter and spring of 1998.

The objectives of Phase I-B Light Vehicle Rollover Research program were to:

1. Develop an understanding of the driver variability effects on test results.
2. Develop an understanding for the effects of outriggers on test results.
3. Develop an understanding for the effects of fuel level on test results.
4. Procure and implement testing with a programmable steering controller. Along with the J-Turn, J-Turn with Pulse Braking, and Fishhook maneuvers, Resonant Steer was to be developed and implemented using the steering controller.
5. Final determination of the maneuvers to be selected for use in Phase II of the Light Vehicle Rollover Research program.

Driver variability effects on test results were evaluated with four test maneuvers: J-Turn (Without Pulse Braking), J-Turn with Pulse Braking, Fishhook Without Pulse Braking, and Fishhook with Pulse Braking.

In general, increasing J-Turn severity, by increasing steering magnitude or vehicle speed, resulted in increasing lateral acceleration and roll angle up to the point of limit response. The J-Turn maneuver was found to be fairly repeatable. Throttle position did appear to make a large difference in test results. To reduce the amount of variability in testing, the drivers will release the throttle in Phase II research upon the initiation of the steering input.

While driver differences produced test-to-test variations for the J-Turn with Pulse Braking maneuver, the overall test results for each driver were fairly similar.

Fishhook testing was performed with the 1990 Toyota 4Runner and 1984 Bronco II. Driver variability did not seem to influence the results found with the 1990 Toyota 4Runner. The Lateral Acceleration at Rollover (LAR) and Minimum Initial Vehicle Speed Required to Produce Two-Wheel Lift values were very similar for the three drivers. The 1984 Ford Bronco II data were more scattered, but this scatter appears to be more related to tire wear (on the shoulder) issues than it does to driver differences. Replacement of tires on a regular basis will be an important issue in Phase II testing.

The range of LAR values for the Fishhook with Pulse Braking tests was much larger than that found for the J-Turn with Pulse Braking maneuver as was the coefficient of variation. The driver controlled results suggest that the Fishhook with Pulse Braking maneuver did not provide any further information for determining the rollover propensity of vehicles than the J-Turn with Pulse Braking maneuver. Therefore, it was decided that this maneuver would not be studied in Phase II of this rollover research program.

Outrigger effects were studied using three different driver controlled maneuvers: the Fishhook Without Pulse Braking, the Fishhook With Pulse Braking, and Sinusoidal Sweep. Up to three outrigger conditions were evaluated with each maneuver: ballasted outriggers, normal outriggers (unballasted), and/or no outriggers.

For the Fishhook Without Pulse Braking tests, the ballast added to the outriggers did not appear to have a strong effect on the calculated LAR values, producing only slightly different LAR values for the limited number of tests sequences conducted. This was also true for the Fishhook with Pulse Braking tests. Sinusoidal Sweep tests results were studied using frequency domain techniques. The outriggers tend to dampen the response at higher frequencies and increase the response at lower frequencies. These changes appear to be relatively small especially for the normal outrigger case versus the no outrigger case.

Two drivers performed both low fuel and full fuel level tests. Fuel level did not appear to have a strong influence on test results. The LAR and Minimum Initial Speed Required to Produce Two-Wheel Lift values were very similar for the two fuel level conditions. Since there appeared to be no major difference in response, all testing in Phase II will be done with a full fuel level for testing convenience.

Steering controller tests were performed using three maneuvers: J-Turn with Pulse Braking, Fishhook without Pulse Braking, and Resonant Steer. This testing proved quite valuable in determining the Phase II test matrix. Two categories of testing will be performed in Phase II: Vehicle Characterization Maneuvers and Untripped Rollover Propensity Maneuvers.

As the name implies, the purpose of the Vehicle Characterization Maneuvers is to characterize the vehicle dynamics of each test vehicle, i.e., determine some of the basic handling characteristics of the vehicle. There are two types of Vehicle Characterization Maneuvers. The first type can be used to determine the frequency response function to characterize the test vehicle transient dynamic response. The second type can be used to measure the test vehicle's steady-state, lateral, dynamic properties. Two types of frequency response tests were developed: Pulse Steer and Sinusoidal Sweep. Two types of vehicle lateral dynamic characterization tests will be performed: Slowly Increasing Steer and Slowly Increasing Speed.

The five Untripped Rollover Propensity Maneuvers developed were: J-Turn, J-Turn with Pulse Brake, Fishhook #1, Fishhook #2, and Resonance Steer.

1.0 INTRODUCTION

1.1 Relationship to Previous Phase of Research

The research described in this report is a natural outgrowth of the work that was performed for Phase I-A of the National Highway Traffic Safety Administration's (NHTSA) 1997 - 1998 Light Vehicle Rollover Research program. The Phase I-A research is described in detail in [1].

When originally planned, NHTSA's 1997 - 1998 Light Vehicle Rollover Research program was to consist of the Phase I research (to be performed during the spring through fall of 1997) which was to develop a set of test maneuvers to be used, and the Phase II research (to be performed during the summer of 1998) which was to use the Phase I maneuver set to measure the on-road, untripped, maneuver induced rollover propensities of a broad range of vehicles. However, preliminary analysis of the Phase I results revealed a number of issues that had to be resolved before the Phase II testing could begin. Therefore, the spring through fall of 1997 testing was renamed the Phase I-A research and additional testing, called the Phase I-B research, was performed during the fall of 1997 and the winter and spring of 1998.

This report covers the work performed for Phase I-B of NHTSA's 1997 - 1998 Light Vehicle Rollover Research program. This research was performed from November 1997 through June 1998.

1.2 Focus of This Study

As was the case for the Phase I-A research of NHTSA's 1997 - 1998 Light Vehicle Rollover Research program, the focus of this study is on-road, untripped rollovers by one class of light vehicles, sport utility vehicles. The reasons for focusing this research on only one class of light vehicle, sport utility vehicles, and for examining only on-road, untripped rollovers are fully discussed in [1].

The goal of this research was to resolve a number of issues that had to be dealt with before the Phase II testing could begin. Therefore, the focus of this study is on testing related issues, principally the development of techniques to maximize test repeatability and the finalization of the Phase II test matrix and test procedures.

1.3 Overview of This Report

This chapter of the report presents the relationship between the current research, Phase I-B of NHTSA's 1997 - 1998 Light Vehicle Research program, and its immediate predecessor, Phase I-A of the same research program. The focus of this report is then briefly discussed. Chapter 2.0, Background, provides a brief summary of Phase I-A results. Chapter 3.0 concludes the introductory portion of this report by presenting the objectives of the current, Phase I-B, study.

The middle portion of the report describes unique features (compared to the Phase I-A research) of the testing that was performed for the Phase I-B study. This portion begins with Chapter 4.0 which details the test vehicles and additional properties measured for these vehicles that were not described in the Phase I-A report. Chapter 5.0 describes changes between the Phase I-B in-vehicle instrumentation that was used during this testing and the in-vehicle instrumentation which was used for the Phase I-A research. Some details of the programmable steering controller are provided as well. Chapter 6 provides details for all of the test procedures conducted. Several different test procedures were used to study driver variability, outrigger effects, and fuel level effects on test results. A steering controller was then used to further refine final test procedures for Phase II.

The next portion of the report contains the results of the Phase I-B research. Chapters 7.0 through 10.0 present results and analysis for the maneuvers and test variables examined during Phase I-B research including driver variability, outrigger effects, and fuel level effects. Chapter 11.0 provides an analysis of the selection of the maneuvers for the final Phase II test matrix. Chapter 12.0 concludes this portion of the report by briefly summarizing the work performed and results found, and presenting the conclusions that can be drawn from this research.

This report concludes with a list of references and appendices.

2.0 BACKGROUND

Rollovers are the second most dangerous type of crash occurring on the highways of the United States. During the eight years 1991 through 1998, analysis of Fatal Analysis Reporting System (FARS) data found that an average of 9,237 people were fatally injured each year in light vehicle rollover crashes. This is second only to the average number of people who died due to head-on collisions. Due to the relatively low number of rollover crashes, when measured by either fatalities or incapacitating injuries per occupant involved, rollover crashes are the most dangerous type of collision for all classes of light vehicles.

Some types of light vehicles are involved in rollover crashes more frequently than others. Small cars have the most rollover crash fatalities of any vehicle class. However, some classes of light vehicles are more common than others in the vehicle fleet. Sport Utility Vehicles (SUVs) have the highest rollover fatality rate per million registered vehicles (more than three times as many as medium and almost five times as many as large cars). Small pickup and standard pickup trucks have the next highest rates respectively. Small and standard vans have very similar rates that fall between those for small cars and those for medium and large cars. The small car rate is two and a half times higher than that for large cars.

Phase I-A testing was performed during the spring through fall of 1997. The following is a brief summary of the results and analysis of the Phase I-A research.

Three vehicles were selected for the Phase I testing. The vehicles selected were a 1984 Ford Bronco II, a 1997 Jeep Cherokee, and a 1990 Toyota 4Runner. These test vehicles were not in new condition. None of the test vehicles necessarily performed as would new vehicles without outriggers. However, this was not important for the Phase I research. The goal of the Phase I research was maneuver selection and test procedure development, not vehicle characterization.

A total of eight test procedures were evaluated in the Phase I-A study: J-Turn (Without Pulse Braking), Brake and Steer, J-Turn With Pulse Braking, Steering Reversal, Toyota Fishhook, Double Lane Change, Split-Mu, and Toyota Fishhook with Pulse Braking. A brief summary of each test maneuver and the test results for each maneuver is contained in the following eight bullets:

- **The J-Turn (Without Pulse Braking)** maneuver consists of a single steering input. For this research, very large handwheel steering input angles (frequently ±330 degrees) were usually used for the J-Turn tests. These large steering angles were chosen to saturate the tires of all of the test vehicles. J-Turn maneuvers were performed with turns to both the left and to the right. The inputs for this test maneuver are very repeatable due to the simple, single steering motion, the mechanical steering stop, and the minimal requirements that this maneuver imposes on the driver.

  For two of the vehicles tested, the Bronco II and the Cherokee, no two-wheel lift was observed during the J-Turn tests. For the 4Runner, minor and moderate two-wheel lifts were observed during the J-Turn tests. In general, increasing J-Turn severity, by increasing steering magnitude or vehicle speed, results in increasing lateral acceleration and roll angle up to the point of limit response. For the Bronco II and Cherokee the limits responses observed were plow outs, while the 4Runner had two-wheel lift.

  The J-Turn tests conducted were found to be fairly repeatable. For any given vehicle, all groups of repeatability tests (similar speed and handwheel inputs), the resulting maximum lateral accelerations varied by at most 0.04 g. and the maximum roll angles varied by at most 0.5 degrees. The J-Turn maneuver is a simple test to conduct relative to other vehicle response handling tests and therefore will be considered in further research.

- **The J-Turn With Pulse Braking** maneuver adds pulse braking to the J-Turn (Without Pulse Braking). J-Turn With Pulse Braking uses the same steering input as a function of time as the J-Turn. The test procedure differs from the test procedure for the J-Turn in that after the driver has turned the steering handwheel to the mechanical steering stop, the throttle was released and a short duration, hard pulse force was applied to the brake pedal. As was the case with the J-Turn (without pulse braking) maneuver, very large handwheel steering input angles (frequently ±330 degrees) were usually used.
  The braking pulse momentarily decreases the lateral force capabilities of the tires, thereby decreasing the vehicle's lateral acceleration. When the braking pulse ends, the lateral force capabilities of the tires increase very rapidly. This sometimes produces vehicle lateral acceleration levels and/or roll angles which surpass those achieved prior to the onset of braking.

These larger lateral accelerations and/or roll angles can result in two-wheel lift for some vehicles that do not have two-wheel lift for the J-Turn (Without Pulse Braking) maneuver.

The applied brake force magnitudes required to produce a sufficient braking pulse (in the opinion of the test driver and test engineers) were much greater for the Jeep Cherokee than for the Ford Bronco II (The Toyota 4Runner was not tested using this maneuver).

Further testing is required to better define and understand the J-Turn With Pulse Braking test. In particular, testing with more consistent brake pulse magnitudes and durations is needed to more carefully determine the effects of the severity of the brake pulse on vehicle responses. The initial test speed appears to be a measure that can be used to quantify a vehicle's rollover propensity. The maneuver may be an indicator of asymmetrical two-wheel lift propensity (dependent on direction of steer). For these reasons, the J-Turn With Pulse Braking maneuver is a good candidate for use as a potential dynamic rollover propensity test procedure. As such, further development of this maneuver during the dynamic rollover research program was recommended.

- **The Brake and Steer** maneuver increases maneuver complexity by adding sustained braking to the J-Turn (without pulse braking). Brake and Steer uses the same steering input as a function of time as does the J-Turn. For all but two of these tests, the brakes were applied at the same time as the steering input. For the other two tests, the brakes were applied well after the steering handwheel had reached the steering stop. As was the case with the J-Turn maneuver, very large handwheel steering input angles (frequently ±330 degrees) were usually used for the Brake and Steer tests. No electronic or mechanical assistance was given to help the driver make the brake application repeatable.

  During analysis of the first vehicle's Brake and Steer testing, the well known fact that applying and maintaining hard braking during steering decreases the lateral force capabilities of the tires was recognized. This reduces the lateral acceleration of the vehicle and the potential for two-wheel lift. As a result, only the Toyota 4Runner was tested using this maneuver. Under hard braking the roll angle, yaw rate, and lateral acceleration decrease rapidly. These responses first overshoot the zero value and then return to zero as the vehicle plows to a stop. Delayed braking allows the roll angle and lateral acceleration to build up to greater levels than the simultaneous steering and braking cases, to the point where two-wheel lift can occur. However, upon the initiation of heavy braking the roll angle, yaw rate, and lateral acceleration reduce to zero as the vehicle plows to a stop.

Since sustained braking tends to decrease the rollover potential for the vehicle, it has been decided that this maneuver will not be further developed.

- **The Steering Reversal** maneuver consists of two steering inputs; the steering handwheel is first turned in one direction and then is rapidly reversed resulting in a turn in the opposite direction. The initial steering movement can be either to the left or to the right. There are an infinite number of combinations of initial and second steering magnitudes that can be used with this test procedure. Test severity can be increased by increasing the magnitudes of the steering inputs, raising the initial vehicle speed, or both. Initial testing for this maneuver was performed using the mechanical steering stop. Unfortunately, the mechanical steering stop was found to hinder the driver's ability to perform the maneuver. No electronic or mechanical assistance was given to help the driver make the steering inputs repeatable. As a result the steering movements were not as repeatable as was the steering input for the J-Turn.

  The Toyota 4Runner was the only vehicle tested using this maneuver. The differences between non-two-wheel lift and two-wheel lift cases for this maneuver were faster vehicle speeds, larger steering magnitudes, and the speed of the steering reversal. Only a small fraction of the infinite number of possible first and second steering input magnitudes were tested in this evaluation.

  The Toyota Fishhook test procedure is also a steering reversal type maneuver which replaced the Steering Reversal maneuver.

- **The Toyota Fishhook** maneuver is detailed in Toyota Engineering Standard TS-A1544 [2]. This test procedure is designed to produce two-wheel lift by imparting to the vehicle a rapid steering reversal that causes the vehicle to be at or near maximum lateral acceleration in one direction due to the initial steer and then rapidly taken to maximum or near maximum lateral acceleration in the other direction. This rapid change in lateral acceleration direction also imparts a large angular momentum change to the chassis due to the vehicle leaning at a relatively large angle to one side and then being forced to lean in the opposite direction. The combination of the change in direction for lateral acceleration and the large roll angular momentum can produce two-wheel lift. The initial handwheel steering input used for this research was approximately 270 degrees. The second steer is to (or close to) the steering lock in the opposite direction from the initial steer. The Toyota Fishhook is run starting with relatively low course entry speeds. The course entry speed is then gradually increased for each successive run until several runs with two-wheel lift are produced. If two-wheel lift cannot be produced at any speed with just steering input, then pulse braking can be added. The addition of pulse braking is discussed in the eighth bullet.

All three Phase I-A test vehicles had two-wheel lift when subjected to the Toyota Fishhook maneuver. For the 4Runner, the Lateral Acceleration for Rollover data is confounded by secondary roll angle peaks. Testing was conducted in only one direction for this vehicle as well. The Bronco II's rollover propensity seems to be highly related to tire wear effects. This vehicle would only produce two-wheel lift after significant tire wear was observed; shoulder wear in particular. Testing with new tires at speeds higher than those that produced two-wheel lift with worn tires, did not result in two-wheel lift, although large front wheel lift was noted. The Cherokee's rollover propensity seems to be an asymmetrical phenomenon, depending on the direction of steering input (only lifted two-wheels with left-then-right steering inputs). Steering rate could also be a possible explanation. Further and more refined testing would be required to determine a good explanation for the difference in left-then-right versus right-then-left steering inputs for the Cherokee.

Although not as simple to conduct as the J-Turn maneuver, the Toyota Fishhook is a relatively easy test to conduct. This maneuver is expected to be further developed during subsequent phases of the the dynamic rollover research program, with special focus being applied to driver effects, tire wear issues, and the timing of the steering reversal. It is believed that a steering controller may be necessary to achieve a consistent steering profile that could be used to evaluate a wide range of vehicles. This maneuver has the potential for evaluating the on-road, untripped rollover propensity of vehicles and it has been decided that it should be further studied and developed.

- **For the Double Lane Change** maneuver, the test driver steers the vehicle through an entrance lane, turns left to avoid the single cone in the second lane, turns right to return to the original lane, and then straightens the vehicle to leave the course via an exit lane. An infinite number of cone placements are possible for a Double Lane Change maneuver. Note that picking a single Double Lane Change course for all vehicles may not be advisable since any given course geometry may excite the natural frequency of some, but not all, vehicles. This type of test can produce dramatically different results depending on the test driver's "steering style" for negotiating the course.

  Two of the three test vehicles experienced two-wheel lift while attempting double lane changes. All three courses utilized for Toyota 4Runner testing produced two-wheel lift, although it was usually minor. One 70/70/14 test, however, did produce major two-wheel lift with the 4Runner. Tire wear appears to be related to the Bronco II's rollover propensity. Two-wheel lift was observed only once for this vehicle, and was achieved on a tire set that had been used to complete numerous runs. After four new tires were installed (equivalent to those which they replaced in dimension and manufacturer), the same course that produced severe two-wheel lift no longer did so–even with identical vehicle speeds and nearly equivalent handwheel inputs. The Jeep Cherokee did not exhibit two-wheel lift in any course layout, even at very high lateral accelerations and with steering inputs nearly identical to those used for the other vehicles.

  Due to the path-following nature of the double lane change maneuver, successfully completing a given course can be very driver-dependent, as there are infinite combinations of steering inputs that could be utilized. The "technique" one driver chooses to employ may be very different than another driver, yet they both complete the maneuver successfully. Previous NHTSA research has investigated the relationship between test driver and two-wheel lift propensity, and confirms the occurrence of this phenomenon [3]. Steering inputs found to induce two-wheel lift in one vehicle, may not induce the same response from another vehicle. Given the complexities associated with the Double Lane Change maneuver relative to the Toyota Fishhook and since the Toyota Fishhook was able to produce two-wheel lift in a greater number of test vehicles, it was recommended that the Double Lane Change Maneuver not be further developed.

- **The Split-Mu Off-Road Recovery Simulation** was developed to try and simulate a scenario that has been documented in the rollover crash data collected by NHTSA. This maneuver simulates the return of a vehicle that has two wheels off the road to having all four wheels on the road surface. A more realistic simulation would require the two wheels off the road surface to climb a lip as they re-entered the road surface. This lip was not simulated to reduce test complexity and variability. For this maneuver, the vehicle is driven onto a split-coefficient-of-friction (split-mu) surface, i.e., the tires on the right side of the vehicle are on the low coefficient-of-friction, wet-epoxy surface and the tires on the left side are on the higher coefficient-of-friction dry-asphalt surface. The driver then turns the vehicle to the left to bring all four tires on to the dry-asphalt surface. This is followed by a turn to the right to try and keep the vehicle within a two lane width boundary (24 feet).

  Very few tests produced two-wheel lift with this maneuver and the driver inputs were not controlled enough to produce repeatable results. A better steering stop design could be used to control the first steering input, but even then the driver has a lot of freedom on how to perform the second and third steering inputs because the vehicle path is not heavily constrained by cones. This test also requires two different test surfaces and since test surface friction ratings can change with time, weather, amount of water (on low coefficient surface), etc., the amount of variability in test results would be expected to increase over a test run on a single surface.

  It was noted during processing, that the data collected from Split-Mu testing was very similar to that from the Steering Reversal testing. A comparison of similar tests from these two maneuver types suggests that the Steering Reversal maneuver is at least as severe if not more so than the Split-Mu maneuver. Vehicle yaw effects on a split-mu surface may potentially increase rollover propensity, but this was not observed in this limited study.

  Due to the complexities associated with this maneuver, it was recommended that the Split-Mu maneuver not be further developed.

- **The Toyota Fishhook With Pulse Braking** maneuver uses the same course and steering input as a function of time as does the Toyota Fishhook Without Pulse Braking maneuver. The test procedure differs from the test procedure for the Toyota Fishhook Without Pulse Braking in that after the driver has completed the second steering movement, a short duration, hard pulse is applied to the brake pedal. The pulse braking causes a sharp decrease in the lateral acceleration capabilities of the tires as the brakes are applied followed by a rapid increase as the brakes are released. This rapid increase in the lateral acceleration can produce lateral accelerations that are significantly higher than the lateral acceleration prior to the application of the brakes. Pulse braking can also produce large momentum changes because the chassis roll angle decreases as the brakes are applied and can rapidly increase as the brakes are released.

The Toyota 4Runner had two-wheel lift during the Fishhook without Pulse Braking testing, therefore, no Fishhook with Pulse Braking tests were conducted with this vehicle. Even though the Ford Bronco II had two-wheel lift without pulse braking, the two-wheel lift appeared to be related to tire wear. Therefore, pulse braking tests were conducted with this vehicle. Two-wheel lift was readily achieved for the Bronco II when pulse braking was added. This is not surprising given that pulse braking also caused two-wheel lift when added to the J-Turn maneuver. During the course of testing it was noted that the Jeep Cherokee had two-wheel lift prior to the initiation of pulse braking during the steering reversal. In these cases the brake pulse occurred during two-wheel lift. The pulse resulted in bringing the two wheels back down and the Cherokee did not lift wheels again.

It does not appear that the Toyota Fishhook with Pulse Braking gives any greater indication of rollover propensity than the combination of the Toyota Fishhook (without Pulse Braking) and the J-Turn with Pulse Braking, although the Bronco II did have a higher level of two-wheel lift for the Toyota Fishhook with Pulse Braking maneuver than it did for the J-Turn with Pulse Braking maneuver in Phase I-A testing. The Toyota Fishhook with Pulse Braking has even more primary input variables than the J-Turn with Pulse Braking. All of these inputs create a more difficult maneuver for the driver to perform.

Although there are many complexities with the Toyota Fishhook with Pulse Braking maneuver, it is recommended that this maneuver be further evaluated in Phase I-B of NHTSA's Light Vehicle Dynamic Rollover Research program. A focus of this research should be to see if this maneuver provides any more information than that attainable with the simpler Toyota Fishhook (without Pulse Braking) and J-Turn with Pulse Braking maneuvers. If not, this maneuver should not be evaluated further.

3.0 STUDY OBJECTIVES

A goal of the National Highway Traffic Safety Administration (NHTSA) is to reduce the number of fatalities and injuries that are due to rollover crashes. To achieve this goal, NHTSA is conducting research programs both to reduce the number of rollover crashes that occur and to mitigate the adverse consequences when rollover crashes do occur. The current study is part of NHTSA's research to reduce the number of rollover crashes.

To reduce the number of rollover crashes, NHTSA is working to develop an information program which will make consumers more aware of vehicle make/models with a high rollover propensity. One key step towards developing a rollover propensity consumer information program is the development of a methodology for determining a vehicle's rollover propensity. This study focuses on the development of such a methodology.

This report covers the work performed for Phase I-B of NHTSA's 1997 - 1998 Light Vehicle Rollover Research Program. This research was performed from November 1997 through June 1998. During the latter part of Phase I-A, it was decided that a steering controller should be purchased to provide more repeatable steering inputs. While waiting for delivery of the steering controller, several studies were conducted to evaluate driver, outrigger, and fuel level effects on test results.

The objectives of Phase I-B Light Vehicle Rollover Research program were to:

1. Develop an understanding of the driver variability effects on test results.

2. Develop an understanding for the effects of outriggers on test results.

3. Develop an understanding for the effects of fuel level on test results.

4. Procure and implement testing with a programmable steering controller. Along with the J-Turn, J-Turn with Pulse Braking, and Fishhook maneuvers, Resonant Steer was to be developed and implemented using the steering controller.

5. Final determination of the maneuvers to be selected for use in Phase II of the Light Vehicle Rollover Research program.

4.0 TEST VEHICLES

4.1 Vehicles Selected

Three vehicles were selected for the Phase I-A testing: a 1984 Ford Bronco II, a 1997 Jeep Cherokee, and a 1990 Toyota 4Runner. It was initially intended to test all three vehicles in Phase I-B, but due to time constraints the Cherokee was not tested. The Phase I-A report documents the condition of these vehicles and the selection process [1]. As stated in the Phase I-A report, none of the test vehicles necessarily performed as would have new vehicles without outriggers. However, the goal of this research was maneuver selection and test procedure development, not vehicle characterization.

4.2 Static and Dynamic Rollover Metric Values for the Test Vehicles

Each of the test vehicles was tested by S.E.A., Inc. on the Vehicle Inertial Measurement Facility (VIMF) and Tilt Table. The 1984 Ford Bronco II was tested on the VIMF both with and without outriggers, while the 4Runner was tested on the VIMF only without outriggers and with the 31x10.50R15LT tire size. The 1990 Toyota 4Runner has two sizes of original equipment tires, 31x10.50R15LT and P225/75R15. Both tire sizes were used for the Phase I-B research. Both the Bronco II and 4Runner were tested on the S.E.A. Tilt Table both with and without outriggers. Both tires sizes for the 4Runner were tested. The results for most of this testing were given in the Phase I-A report with the exception of the smaller tire P225/75R15 Toyota 4Runner Tilt Table results. For comparison purposes, the Tilt Table results for both Toyota 4Runner tires sizes are given in Table 4.1.

Table 4.1: Tilt Table Ratio Values for the Toyota 4Runner

Tire Size	Tilt Table Ratio	
	Without Outriggers	With Outriggers
31x10.50R15LT (larger)	0.91	0.92
P225/75R15 (smaller)	0.91	0.92

It is not intuitive that the Tilt Table Ratio for the two tire sizes would be the same. The smaller tires (P225/75R15) lower the chassis of the vehicle by approximately 1 inch which should increase the Tilt Table Ratio, but the smaller tires reduced the outside-of-tire to outside-of-tire distance by approximately 2.5 inches thus reducing the distance of the tripping point to the center of gravity which would tend to decrease the Tilt Table Ratio. The smaller tires also appear to be more compliant because the chassis lateral deflection just prior to lift off was approximately ½ inch greater (2 & 1/8 inches versus 1 & 5/8 inches) for the smaller tire which would also tend to lower the Tilt Table Ratio. The net effect of these influences is no change in the Tilt Table Ratio for the two tire sizes.

5.0 VEHICLE INSTRUMENTATION

The test vehicles were instrumented the same as they were in Phase I-A with the exception of a vehicle steering controller that was used for some of the testing. The Phase I-A report [1] contains more details about the instrumentation used and the instrumentation installation.

5.1 Sensors and Sensor Locations

Table 5.1 is a list of the sensors used to measure vehicle responses that were recorded by the in-vehicle data acquisition system.

The data acquisition was started by an event trigger which consisted of a SunX RS-120H-1 optical sensor mounted on each vehicle's front bumper detecting a reflective plate which was placed at a pre-selected location at the beginning of each test maneuver's course. When the steering controller was used, the data acquisition was started using the computer keyboard.

Table 5.1: Vehicle Sensor Information

Vehicle Channel	Sensor Type	Sensor Range	Sensor Manufacturer	Sensor Model Number
Lateral Acceleration	Accelerometer	" 2g	Setra	141A
Longitudinal Acceleration	Accelerometer	" 2g	Setra	141A
Vertical Acceleration	Accelerometer	" 2g	Setra	141A
Roll Rate	Gas Beam Rate Sensor	" 50 deg/sec	Humphrey	RT10-0127-1
Yaw Rate	Gas Beam Rate Sensor	" 50 deg/sec	Humphrey	RT10-0127-1
Left Vertical Displacement	Ultrasonic Position	4 - 22 inches	Massa	M4000
Right Vertical Displacement	Ultrasonic Position	4 - 22 inches	Massa	M4000
Handwheel Steer Angle	10 Turn Potentio-meter With 2 to 1 Gear Ratio	Lock-to-lock	Servo Systems	7603-424-0
Handwheel Steer Torque	Hollow Reaction, Strain Gauge	" 600 in-lb	Himmelstein	RTM2030
Brake Pedal Force	Strain Gauge Load Cell	0 - 300 lbs	GSE	3100A
Event Trigger	Optical Position Detector	Not Applicable	SunX	RS-120H-1
Vehicle Speed	Tachometer Generator	0 - 60 mph	Servo-Tek	SN7466F-1

5.2 Programmable Steering Machine

During some of the Phase I-B testing, the vehicle was equipped with an Automotive Testing, Inc. (ATI) Programmable Steering Machine. This device was used to generate handwheel steering inputs throughout all of this testing. The capabilities of this machine are fully described in [4] and [5]. In brief, to quote from [5],

> "The ATI Programmable Steering Machine is an easily-installed, battery-powered, "series servo second steering wheel". The steering machine is designed to execute any 16384-step steering program with force and velocity capabilities significantly greater than those of the human driver. Its EPROM memory contains sixteen separate programs, which can be programmed to duplicate any steering input with fidelity and repeatability. During the execution of a program, the handwheel is mechanically "grounded" to eliminate driver interference with measurement of steering angles and torques. The program also outputs auxiliary signals that can be used to control vehicle throttle and brakes, data recorders, or other devices."

The ATI Programmable Steering Machine can turn the steering handwheel through the entire lock-to-lock range. Feedback control is used to generate the precise steering input desired. Handwheel steer rates of up to 1800 degrees per second and handwheel steer torques of up to 50 Newton-meters, in either direction, can be generated. The ATI Programmable Steering Machine includes integral handwheel steer angle and handwheel steer torque sensors. The handwheel steer angle transducer has a resolution of ±0.10 degrees and the handwheel steer torque sensor has an accuracy of 0.3 Newton-meters.

6.0 TEST PROCEDURES

A total of five test maneuvers were evaluated during the Phase I-B testing: J-Turn, J-Turn With Pulse Braking, Fishhook Without Pulse Braking, Fishhook With Pulse Braking, and Resonant Steer. Driver, fuel loading, and outrigger effects were studied using driver inputs. After the controller was made available, testing was performed to develop the J-Turn, Fishhook, and Resonant Steer procedures that were implemented in Phase II research. The types of testing conducted with these maneuvers will be outlined in the following sections.

6.1 Driver Variability Test Procedures

Driver variability effects on test results were evaluated with four test maneuvers: J-Turn (Without Pulse Braking), J-Turn with Pulse Braking, Fishhook Without Pulse Braking, and Fishhook with Pulse Braking. Each of these test procedures are described in the following sub-sections. The Phase I-A report [1] discusses these test maneuvers in more detail.

6.1.1 J-Turn (Without Pulse Braking) Maneuver - Driver Controlled Test Procedures

The J-Turn (Without Pulse Braking) maneuver consists of a single steering input. From Phase I-A it was found that the steering inputs for this test maneuver are very repeatable due to the simple, single steering motion, the mechanical steering stop, and the minimal requirements that this maneuver imposes on the driver. The Toyota 4Runner had minor and moderate two-wheel lifts during Phase I-A J-Turn testing. The other vehicles tested did not have two-wheel lift. The J-Turn test results were found to be fairly repeatable. For any given vehicle, all groups of repeatability tests (similar speed and handwheel inputs), the resulting maximum lateral accelerations varied by at most 0.04 g. and the maximum roll angles varied by at most 0.5 degrees. The J-Turn maneuver was a simple test to conduct and therefore it was decided it would be studied further.

For Phase I-B testing, a very limited number of J-Turn tests were performed with the 1990 Toyota 4Runner to study driver effects on repeatability for this maneuver. The Toyota 4Runner was the only vehicle in Phase I-A that had two-wheel lift in this maneuver. Therefore the Bronco II was not tested. Two drivers performed one set of tests for each steering direction. A set of tests consists of a series of tests conducted at increasing initial speed until two-wheel lift was achieved. A new set of tires was used for each driver. Tests were conducted in both the left and right steer directions on each set of tires. All of the tests were conducted with 330 degrees of steering input. The drivers were told to maintain throttle for these tests, but due to the large steering angles, speed was scrubbed off during the maneuver.

6.1.2 J-Turn With Pulse Braking Maneuver - Driver Controlled Test Procedures

The J-Turn With Pulse Braking maneuver adds pulse braking to the J-Turn (without pulse braking). J-Turn With Pulse Braking uses the same steering input as a function of time as the J-Turn maneuver. The test procedure differs from the test procedure for the J-Turn in that after the driver has turned the steering handwheel to the mechanical steering stop, the throttle was released and a short duration, hard pulse force was applied to the brake pedal. The braking pulse momentarily decreases the lateral force capabilities of the tires, thereby decreasing the vehicle's lateral acceleration. When the braking pulse ends, the lateral force capabilities of the tires increase very rapidly. This sometimes produces vehicle lateral acceleration levels and/or roll angles which surpass those achieved prior to the onset of braking. These larger lateral accelerations and/or roll angles can result in two-wheel lift for some vehicles that do not have two-wheel lift for the J-Turn (without pulse braking) maneuver.

From Phase I-A testing, it was decided that further testing was required to better define and understand the J-Turn With Pulse Braking test. In particular, testing with more consistent brake pulse magnitudes and durations was needed to more carefully determine the effects of the severity of the brake pulse on vehicle responses. The initial test speed appeared to be a measure that could be used to quantify a vehicle's rollover propensity.

A limited number of J-Turn with Pulse Braking tests were performed with the 1984 Ford Bronco II in Phase I-B (The Bronco II was tested because the Toyota 4Runner had two-wheel lift for the J-

Turn, without Pulse Braking, maneuver.). Two drivers conducted the testing. One of the drivers completed two sets of tests for each steering direction while the other completed one set. A new set of tires was used for each driver and test set. Tests were conducted in both the left and right steer directions on each set of tires. All of the tests were conducted with 330 degrees of steering input.

6.1.3 Fishhook Without Pulse Braking Maneuver - Driver Controlled Test Procedures

The Toyota Fishhook maneuver is detailed in Toyota Engineering Standard TS-A1544 [2]. This test procedure is designed to produce two-wheel lift by imparting to the vehicle a rapid steering reversal that causes the vehicle to be at or near maximum lateral acceleration in one direction due to the initial steer and then rapidly taken to maximum or near maximum lateral acceleration in the other direction. This rapid change in lateral acceleration direction also imparts a large angular momentum change to the chassis due to the vehicle leaning at a relatively large angle to one side and then being forced to lean in the opposite direction. The combination of the change in direction for lateral acceleration and the large roll angular momentum can produce two-wheel lift.

All three Phase I-A test vehicles had two-wheel lift when subjected to the Toyota Fishhook maneuver. For the 4Runner, the Lateral Acceleration for Rollover data were confounded by secondary roll angle peaks. The Bronco II's rollover propensity seemed to be highly related to tire wear effects. This vehicle would only produce two-wheel lift after significant tire wear was observed; shoulder wear in particular. Testing with new tires at speeds higher than those that produced two-wheel lift with worn tires, did not result in two-wheel lift, although large front wheel lift was noted. Phase I-A results suggested that this maneuver should be further developed during the dynamic rollover research program, with special focus being applied to driver effects, tire wear issues, and the timing of the steering reversal. It was believed that a steering controller might be necessary to achieve a consistent steering profile that could be used to evaluate a wide range of vehicles.

For Phase I-B, Fishhook testing was performed by three drivers using both the 1990 Toyota 4Runner and 1984 Bronco II. The driver tests focused on driver repeatability, the influence of fuel level on results, and the influence of outriggers on results. The effect of tire size for the Toyota 4Runner was also examined.

The initial testing examined driver repeatability. The number of test sets run for each driver/vehicle combination is given in Table 6.1. All of these tests were conducted with a low fuel level (less than 1/4 of a tank). For each test set, tests were conducted with both a right-then-left steering input and a left-then-right steering input. It was intended that testing be conducted until three tests with two-wheel lift were achieved so a Lateral Acceleration at Rollover (LAR) value could be determined. The initial steering magnitude was 270 degrees and was controlled using a steering stop.

Table 6.1: Number of Fishhook Without Pulse Braking Test Sets Conducted for Each Driver/Vehicle Combination

Vehicle	Driver	Number of Test Sets
1990 Toyota 4Runner	A	2
	B	1
	C	2
1984 Bronco II	A	3
	B	1
	C	1

Fishhook tests were also performed with the 4Runner using the smaller tire size (P225/75R15) that is available for the vehicle. The initial tests were done with a smaller rim size, but after a tire debeading, the smaller tires were mounted on the rims normally used for the larger tire size (31x10.50R15LT). All other tests were done with the larger tire size. All of the smaller tire tests were performed by the same driver (Driver A).

6.1.4 Fishhook With Pulse Braking Maneuver - Driver Controlled Test Procedures

The Toyota Fishhook With Pulse Braking maneuver uses the same course and steering input as a function of time as does the Toyota Fishhook Without Pulse Braking. The test procedure differs from the test procedure for the Toyota Fishhook Without Pulse Braking in that after the driver has completed the second steering movement, a short duration, hard, pulse was applied to the brake pedal. The pulse braking causes a sharp decrease in the lateral acceleration capabilities of the tires as the brakes are applied and then a sharp increase as the brakes are released. This rapid increase in the lateral acceleration can produce lateral accelerations that are significantly higher than the lateral acceleration prior to the application of the brakes. Pulse braking can also produce large angular momentum changes because the chassis roll angle decreases as the brakes are applied and can rapidly increase as the brakes are released.

For Phase I-A testing, the Toyota 4Runner had two-wheel lift during the Fishhook without Pulse Braking testing, therefore, no Fishhook with Pulse Braking tests were conducted with this vehicle. Even though the Ford Bronco II had two-wheel lift without pulse braking, the two-wheel lift appeared to be related to tire wear. Therefore, with pulse braking tests were conducted with this vehicle. Two-wheel lift was readily achieved for the Bronco II when pulse braking was added. In Phase I-A, it did not appear that the Toyota Fishhook with Pulse Braking maneuver gave any greater indication of rollover propensity than the combination of the Toyota Fishhook (without Pulse Braking) and the J-Turn with Pulse Braking. Although there were many complexities with the Toyota Fishhook with Pulse Braking maneuver, it was recommended that this maneuver be further evaluated in Phase I-B of NHTSA's Light Vehicle Dynamic Rollover Research program. A focus of this research should be to see if this maneuver provides any more information than that attainable with the simpler Toyota Fishhook (without Pulse Braking) and J-Turn with Pulse Braking maneuvers. If not, this maneuver should not be evaluated further.

For Phase I-B, Fishhook with Pulse Braking tests were performed by three drivers using the 1984 Bronco II. The number of test sets for each driver/vehicle combination is given in Table 6.2. All of these tests were conducted with a low fuel level (less than 1/4 of a tank). For each test set, tests were conducted with both a right-then-left steering input and a left-then-right steering input. It was intended that testing be conducted until three tests with two-wheel lift were achieved so a Lateral Acceleration at Rollover (LAR) value could be determined.

Table 6.2: Number of Fishhook With Pulse Braking Test Sets Conducted for Each Driver/Vehicle Combination

Vehicle	Driver	Number of Test Sets
1984 Bronco II	A	3
	B	1
	C	1

6.2 Test Procedures to Examine the Effect of Outriggers on Test Results

Outrigger effects were studied using three different maneuvers: Fishhook Without Pulse Braking, Fishhook with Pulse Braking, and Sinusoidal Sweep. The procedures used for each of these maneuvers are given in the following sub-sections.

6.2.1 Fishhook Without Pulse Braking Test Procedures - Outrigger Effects

Outrigger effects were studied using the Fishhook Without Pulse Braking maneuver by placing sandbag weights on the outriggers. A total of 100 lbs was added to each outrigger. This allowed the simulation of a heavier outrigger compared to the outriggers used in this research. Driver A conducted one set of tests with the ballasted outriggers using the Ford Bronco II, while Driver C conducted one set with the Toyota 4Runner. These tests were performed in a similar manner to those conducted for the Fishhook Without Pulse Braking maneuver described in Section 6.1.3 with the only difference being the extra weight placed on the outriggers. This allowed the results of the ballasted outrigger tests to be compared to those without ballast.

The effect of the ballast on vehicle inertial parameters is given in Table 6.3 for the Bronco II. Base vehicle inertial parameters were measured for the 4Runner, but normal outrigger measurements were not conducted. The base vehicle and vehicle with standard outrigger parameters were measured by

S.E.A. Inc. while the ballasted outrigger parameters were calculated using the measured outrigger parameters and using the principle axis theorem knowing the mass and position of the sandbags. The effect of suspension deflection due to the extra weight was not accounted for in this analysis.

Table 6.3: 1984 Ford Bronco II Inertial Parameters for Various Vehicle Configurations

Inertial Parameter	Base Vehicle Value	Normal Outriggers		Ballasted Outriggers	
		Value	Percent Increase vs. Base Vehicle	Value	Percent Increase vs. Base Vehicle
Weight (lbs)	3531	3656	3.5	3856	9.2
Ixx (ft.lb.sec^2)	454	543	19.6	670	47.6
Iyy (ft.lb.sec^2)	1786	1957	9.6	2248	25.9
Izz (ft.lb.sec^2)	1874	2127	13.5	2545	35.8

6.2.2 Fishhook With Pulse Braking Test Procedures - Outrigger Effects

Outrigger effects were also studied using the Fishhook With Pulse Braking maneuver. Driver A conducted one set of tests with the ballasted outriggers using the Ford Bronco II. These tests were performed in a similar manner to those conducted for the Fishhook With Pulse Braking maneuver described in Section 6.1.4 with the only difference being the extra weight placed on the outriggers.

6.2.3 Frequency Response Test Procedures - Outrigger Effects

Sinusoidal Sweep tests were performed using driver controlled steering inputs with the 1990 Toyota 4Runner to help determine and understand the effect of outriggers on vehicle response using frequency domain techniques. Tests were performed with no outriggers, normal outriggers, and ballasted outriggers. All testing was conducted at 36 mph. After testing was complete, Fast Fourier Transform techniques are then applied to the data to calculate the vehicle's frequency response functions (yaw rate, roll rate, lateral acceleration, and roll angle) for each vehicle. The Sinusoidal Sweep test procedure is described in more detail in Section 6.4.3 - Resonant Steer Maneuver - Steering Controller Test Procedures.

6.3 Test Procedures to Examine the Effect of Fuel Level on Test Results

The effect of fuel level on test results was evaluated using the Fishhook Without Pulse Braking Test procedure. Tests were performed with a low fuel level and a full fuel level using the Toyota 4Runner. Testing was primarily conducted with a low fuel level. These tests were described in Section 6.1.3 and a listing of the test combinations was given in Table 6.1. A limited number of test sets were conducted with a full fuel level. Both drivers A and C conducted one set of tests with the higher fuel level. For each test set, tests were conducted with both a right-then-left steering input and a left-then-right steering input. Other than the higher fuel level, the test procedures for the higher fuel level tests were the same as those described in Section 6.1.3 for the low fuel level testing.

6.4 Steering Controller Test Procedures

The steering controller was used to evaluate three test maneuvers: J-Turn with Pulse Braking, Fishhook Without Pulse Braking, and Resonant Steer. Each of these test procedures are described in the following sub-sections. The Phase I-A report [1] discusses the J-Turn with Pulse Braking and the Fishhook Without Pulse Braking test maneuvers in more detail. The Resonant Steer procedure will be presented in detail here.

6.4.1 J-Turn With Pulse Braking Maneuver - Steering Controller Test Procedures

A limited number of J-Turn with Pulse Braking tests were performed with the 1990 Toyota 4Runner using the steering controller. This testing was primarily performed to allow the driver to get used to using the steering controller and to determine how best to use the controller to perform J-Turn (with and without Pulse Braking) testing in Phase II research. The testing was also designed to examine the effect of different levels of pulse braking (magnitude of brake pedal force) on vehicle responses.

For one part of the steering controller study, two sets of tests were performed to see the effect of a lower brake pedal force versus a higher brake pedal force on J-Turn with Pulse Braking overall results, i.e., does a lower brake pedal force require a higher speed to achieve two-wheel lift. The driver was to give a 100 pounds-force pulse for the lower brake force and 200 pounds-force pulse for the higher brake force. All of the testing was performed with a left steering input.

For the second part of the steering controller study, the test speed was kept constant (approximately 40 mph) and the driver was asked to provide varying levels of force ranging from approximately 50 to 250 pounds-force. This part of the study was designed to examine the effects of brake pedal force magnitude on various vehicle responses including, vehicle deceleration, roll angle, lateral acceleration, roll rate, and yaw rate. Left and right steering inputs were performed.

6.4.2 Fishhook Maneuver - Steering Controller Test Procedures

After the steering controller was received, testing was performed to help determine the inputs to be used in Phase II testing. Two studies were conducted to examine the effect of steering reversal timing and steering rates on vehicle response using the Fishhook procedure. The 1990 Toyota 4Runner was the only vehicle tested.

The first study compared two steering profiles by running complete Fishhook test sets, i.e., until three two-wheel lift tests were noted so the Lateral Acceleration at Rollover could be determined.

The first profile had a 270 degree initial steer with a 0.25 second pause followed by a 900 degree steer in the opposite direction (actually to the steering stop which was less than 900 degrees). The second profile had a 180 degree initial steer with a 0.5 second pause followed by a 900 degree steer in the opposite direction (again to the steering stop). The steering rate was 500 deg/sec for each steering profile. The steering profiles are summarized in Table 6.4.

Table 6.4: Fishhook Steering Controller Study I Steering Profiles

Program Number	Initial Steer Angle (deg)	Hold Time (sec)
0	270	0.25
1	180	0.50

For the second study, the variables examined were steering rate, pause before the steering reversal, and replication (tire wear). Two levels of steering rate were used (500 and 750 deg/sec) and four levels of pause (0, .25, 0.5, and 1.0 sec). Four replications were conducted. No tire changes were made during testing so replication could be used to monitor the effects of tire wear. The tests were conducted in a random order for each replication. All testing was conducted at 30 mph. The steering magnitudes were 270 degrees for the initial steer and 600 degrees for the steering reversal. The steering profiles are summarized in Table 6.5.

Table 6.5: Fishhook Steering Controller Study II Steering Profiles

Program Number	Handwheel Rate (deg/s)	Hold Time (sec)
0	500	0.00
1	750	0.00
2	500	0.25
3	750	0.25
4	500	0.50
5	750	0.50
6	500	1.00
7	750	1.00

6.4.3 Resonant Steer Maneuver - Steering Controller Test Procedures

This maneuver is designed to excite a vehicle's roll natural frequency, as determined by using a Pulse Steer or Sinusoidal Sweep maneuver.

The Pulse Steer maneuver collects data due to inputting a short, fairly large, handwheel steering pulse. Fast Fourier Transform techniques are then applied to the data to calculate each vehicle's frequency response function. For this maneuver, the vehicle is initially driven in a straight line. Starting at time 0.0, the Programmable Steering Machine generates a handwheel steering pulse. The steering handwheel is then held at 0 degrees for the remainder of the test. Figure 6.1 shows an example steering handwheel angle as a function of time for this maneuver.

The Sinusoidal Sweep maneuver collects data due to inputting a fixed amplitude, varying frequency handwheel steering sinusoid. Fast Fourier Transform techniques are then applied to the data to calculate each vehicle's frequency response function. For this maneuver, the vehicle is initially driven in a straight line. Starting at time 0.0, the Programmable Steering Machine generates a handwheel steering sinusoid with variable frequency. Figure 6.2 shows an example steering handwheel angle as a function of time for this type of maneuver.

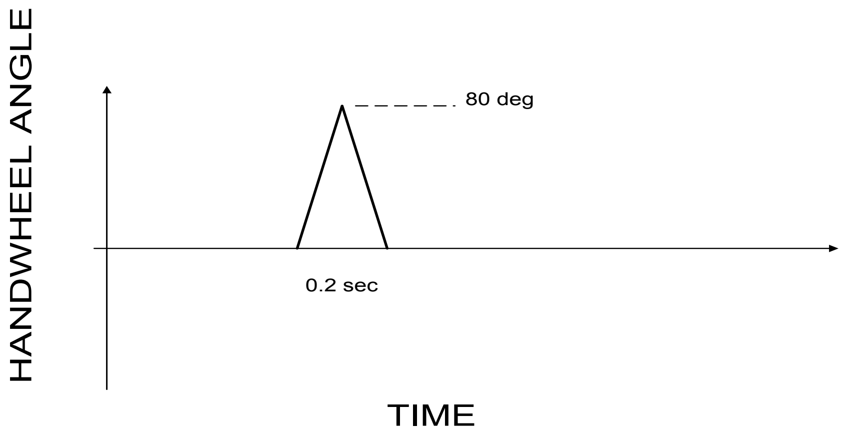


Figure 6.1 – Pulse Steer Handwheel Input

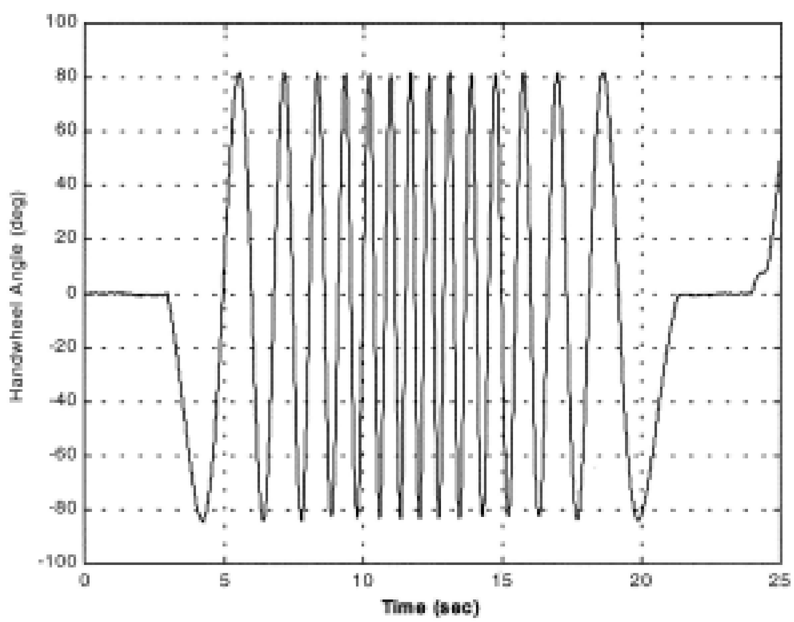


Figure 6.2 -- Handwheel Steering Input for the Sinusoidal Sweep Maneuver

For the Resonant Steer maneuver, the test vehicle is initially driven in a straight line, then the Programmable Steering Machine begins to turn the handwheel back-and-forth through multiple cycles in a sinusoidal manner. The frequency of sinusoidal steering input is equal to the vehicle's measured roll natural frequency. Figure 6.3 shows a typical steering handwheel input as a function of time for this maneuver. This maneuver is performed at a pre-determined initial speed and the test driver applies the throttle in an attempt to hold vehicle speed constant throughout the maneuver.

Pulse Steer, Sinusoidal Sweep, and Resonant Steer testing was performed using the Toyota 4Runner. For all three maneuvers, testing was conducted at 40 and 50 mph. The Pulse Steer tests were conducted in both left and right steer directions. The pulse magnitude was 80 degrees. Two pulse durations were used (0.2 and 0.3 seconds). Two frequency ranges were tested using Sinusoidal Sweep steering inputs: 0.1 to 1.0 Hertz and 0.1 to 2.5 Hertz. The Resonant Steer maneuver was used to perform testing at specific frequencies. The reason for testing at the specific frequencies is discussed in Section 10.3, Resonant Steer Maneuver Test Results and Analysis - Steering Controller Study.

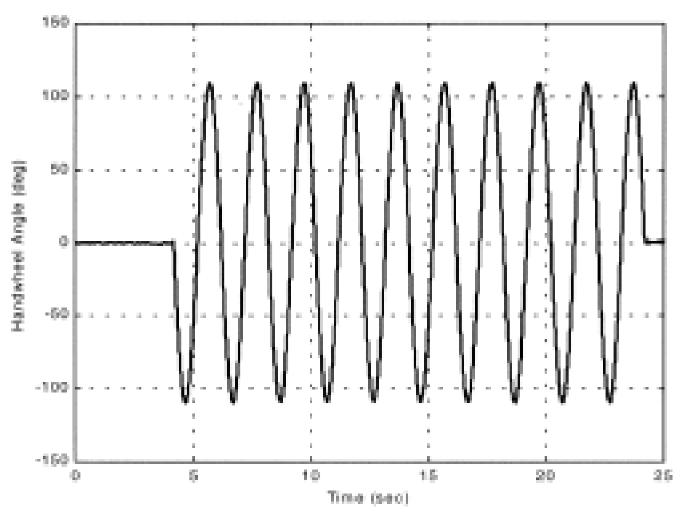


Figure 6.3 -- Handwheel Steering Input for the Resonant Steer Maneuver

7.0 DRIVER VARIABILITY EFFECTS ON TEST RESULTS

Driver variability effects on test results were evaluated with four test maneuvers: J-Turn (Without Pulse Braking), J-Turn with Pulse Braking, Fishhook Without Pulse Braking, and Fishhook with Pulse Braking. The results from testing for each of these test procedures are given in the following sections. For each maneuver, driver variability effects on results are examined. A general assessment of each maneuver is also given.

7.1 J-Turn Maneuver Test Results and Analysis - Driver Effects

A limited number of J-Turn tests were performed by two drivers. The results from these tests are presented below. Driver effects are examined and a general assessment of the J-Turn maneuver is given.

7.1.1 J-Turn Tests Performed for Each Vehicle

As stated in Section 6.1.1, two drivers performed J-Turn tests using the 1990 Toyota 4Runner. Table 7.1 lists some of the results for each test including: Test Number, Steer Direction, Initial Speed, Speed at Maximum Roll Angle, Peak Lateral Acceleration Prior to Peak Roll Angle, Maximum Roll Angle, Maximum Handwheel Rate, Average Handwheel Rate, and Amount of Two-Wheel Lift.

The Initial Speed is determined from the average speed over 0.1 seconds (average of 10 data points) measured at the beginning of each test. The average is taken starting 0.1 seconds before the handwheel angle reaches 50 degrees.

Even though the driver tries to maintain throttle, the vehicle speed drops off during the test due to the large steering inputs. This can be seen in Table 7.1 by comparing the Initial Speed to the Speed at Maximum Roll Angle. The Speed at Maximum Roll Angle is always lower than the Initial Speed. This is especially true for the cases when two-wheel lift occurs. When two-wheel lift occurred, it generally was much later than the initial steering input and after the vehicle had several roll oscillations. The speed and roll angle channels for Test Number 130 are plotted as a function of time in Figure 7.1. The speed drops off as the steering input is applied and maintained. The two-wheel lift happens after four large roll oscillations of the vehicle have occurred. The vehicle speed has dropped by half the initial speed at the point of maximum roll angle. For other tests where the vehicle does not have two-wheel lift, the Speed at Maximum Roll Angle is generally less reduced from the Initial Speed. This is due in part to the Maximum Roll Angle occurring on earlier oscillation peaks for these tests. Throttle position also plays a role and this will be discussed further in Section 7.1.3.

The Peak Lateral Acceleration has been corrected for roll angle. The correction process is fully described in [1].

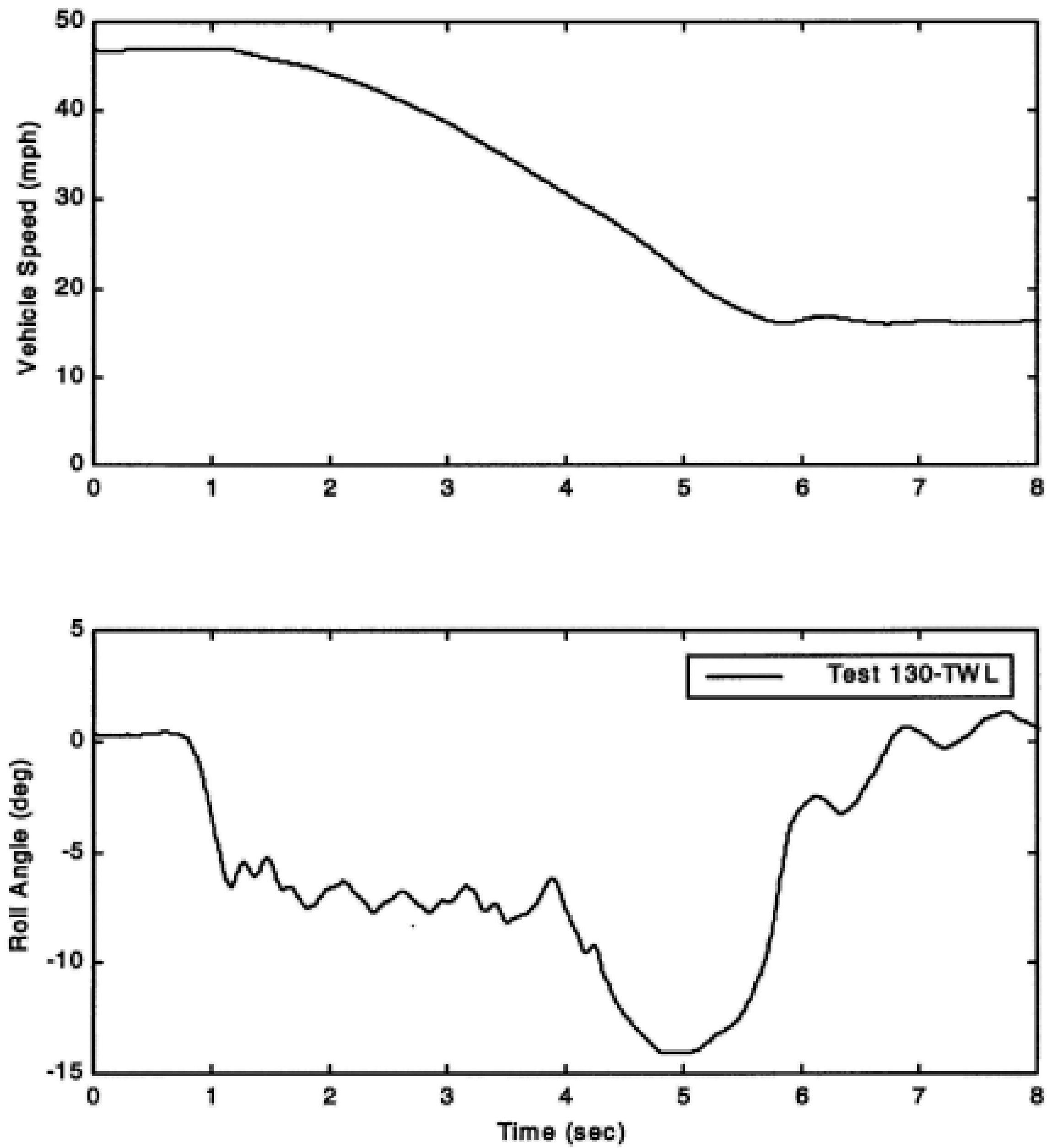


Figure 7.1 -- Vehicle Speed and Roll Angle for 4Runner J-Turn Test Number 130

Table 7.1 -- J-Turn Test Results for the Toyota 4Runner

Driver	Test Number	Steer Direction	Initial Speed (mph)	Speed at Maximum Roll Angle (mph)	Peak Lateral Acceleration Prior to Maximum Roll Angle (g)	Maximum Roll Angle (deg)	Maximum Handwheel Rate (deg/sec)	Average Handwheel Rate (deg/sec)	Amount of Two-Wheel Lift
A	118	Left	36.7	33.9	0.69	7.1	1129	620	None
	119	Left	38.2	Driver overshot the steering stop			978	588	None
	120	Left	38.2	30.1	0.72	7.9	1042	614	None
	121	Left	40.3	31.0	0.77	8.5	917	551	None
	122	Left	40.5	31.0	0.77	8.3	922	550	None
	123	Left	40.4	35.4	0.71	7.9	810	490	None
	124	Left	43.2	40.5	0.70	7.9	902	512	None
	125	Left	44.7	42.1	0.71	8.6	753	480	None
	126	Left	45.8	32.3	0.76	12.4	853	545	Major
	127	Right	41.2	38.9	0.70	7.5	694	511	None
	128	Right	42.6	39.4	0.72	7.9	834	558	None
	129	Right	45.3	38.7	0.74	8.0	854	561	None
	130	Right	46.9	23.1	0.81	14.5	712	512	Major
						Average	877	546	
C	178	Left	38.9	36.9	0.64	7.1	979	628	None
	179	Left	39.4	35.2	0.67	7.1	886	568	None
	180	Left	41.1	38.2	0.66	7.0	867	591	None
	181	Left	44.2	41.6	0.67	7.4	1054	614	None
	182	Left	46.2	41.7	0.69	7.7	920	598	None
	183	Left	48.1	44.2	0.68	7.7	825	564	None
	184	Left	50.6	43.1	0.69	7.9	880	561	None
	185	Left	52.2	44.5	0.75	8.5	938	582	None
	186	Left	54.3	39.9	0.72	9.2	895	571	None
	187	Left	55.7	Handwheel bounced off steering stop			875	574	None
	188	Left	56.4	34.5	0.87	12.4	776	553	Moderate
	189	Right	49.9	43.6	0.76	7.8	864	580	None
	190	Right	51.1	33.2	0.83	13.0	917	571	Major
						Average	898	581	

The average handwheel rate was calculated over the period when the steering rate is first above 100 deg/sec until it decreases to just below 100 deg/sec.

The Amount of Two-Wheel Lift Column lists either Major, Moderate, Minor, or None. These values are assigned after examination of the video for each test run. The definitions of these values are:

Major – Easily discernable two-wheel lift occurred for a significant period of time and the vehicle's outriggers touched the ground during this portion of this test run. Major two-wheel lift can always be observed by the test driver and observers.

Moderate – Easily discernable two-wheel lift occurred for a significant period of time. However, the vehicle's outriggers did not touch the ground at any time during this test run. Moderate two-wheel lift can always be observed by the test driver and observers.

Minor – Minor two-wheel lift is two-wheel lift that occurs only for a brief moment (a fraction of a second) during the test run. Minor two-wheel lift is difficult to discern, and it is not readily apparent during casual viewing of the test run's video. Careful examination of the video, sometimes frame-by-frame analysis, is required to establish when Minor two-wheel lift occurs.

None – Two-wheel lift did not occur during this test run.

The Major Two-Wheel Lifts given in Table 7.1 are somewhat less than some of the Major Two-Wheel Lifts found in Phase I-A research. This is due to the outriggers being set lower for the Toyota 4Runner in Phase I-B research.

7.1.2 The J-Turn and Rollover Propensity

From Phase I-A, it was found that in general, increasing J-Turn severity, by increasing either the magnitude of the Steering Input or the Initial Speed, resulted in increasing maximum corrected lateral accelerations and roll angles up to the point of limit response. For the Ford Bronco II and Jeep Cherokee the limit responses observed were plow outs. The Toyota 4Runner experienced two-wheel lift at the limit response and that is why it was the only vehicle tested using this maneuver in Phase I-B. There was some thought that tire wear may have helped to induce the Toyota 4Runner two-wheel lifts seen in Phase I-A.

The general trend of increasing vehicle Initial Speed resulting in increased Peak Lateral Accelerations and Maximum Roll Angles was also found to be the case in Phase I-B testing. For both drivers, the lateral accelerations and roll angles tended to increase up to the limit response. Both drivers were able to achieve two-wheel lift in both directions for this vehicle. The Initial Speed at which this occurred were different for the two drivers in general. This will be discussed further in the following section.

Tire wear appears to be less of an issue in achieving two-wheel lift for the Toyota 4Runner than what was thought from Phase I-A testing. Although quite a few tests were conducted in the Left Steer direction, these tests did not produce wear on the left side tires (the tires on the inside of the turn). These tests were then followed by a very limited number of Right Steer direction turns that also produced two-wheel lift. The left side tires were on the outside of the turn for these tests and did not have as much wear as the right side tires when two-wheel lift was achieved due to fewer tests being conducted in this direction.

7.1.3 Driver Variability Effects on the Repeatability of the J-Turn Maneuver

In Phase I-A, J-Turn testing was found to be very repeatable. For all the groups of repeatability tests, the resulting maximum lateral accelerations varied by at most 0.04 g. and the maximum roll angles varied by at most 0.5 degrees.

There are two main factors related to the testing that influences the repeatability of the test results. The driver was instructed to turn the handwheel as rapidly as possible into the steering stop. However, there is some variability in the steering rates used for the J-Turns. Also, although the initial speed of each test is well defined and measured, there is some variability in the vehicle longitudinal acceleration at the start of each test. Since cruise control was not used for these tests, in some cases the vehicles may have been accelerating or decelerating slightly at the instant of steering initiation. Also, the driver was asked to maintain throttle during testing. How well the driver maintains throttle can have a tremendous effect on the speed of the vehicle which can in-turn affect other vehicle responses including lateral acceleration and roll angle. This will be discussed further in the following paragraphs. A programmable steering controller and special care to start the tests at constant speed should improve test repeatability.

The initial speed required to produce two-wheel lift was quite different for the two drivers. Driver A had two-wheel lift occur in the mid 40s (mph) for both directions while Driver C required speeds in the low to mid 50s. It is not intuitively obvious why this would be the case. The steering inputs for the two drivers had a similar range of and average values for Maximum and Average Handwheel Rates, as shown in Table 7.1, and therefore are not considered to be an explanation for the differences between the two drivers. An explanation for these differences can be found by examining similar initial speed runs for each of the drivers.

Driver A had two sets of runs that had very similar Initial Speeds. Tests 119 and 120 had the same Initial Speed (38.2 mph) and Tests 121 through 123 had Initial Speeds ranging from 40.3 to 40.5 mph. The driver overshot the steering stop during Test 119 and therefore this test pair cannot be analyzed for comparison purposes.

For Tests 121 through 123, two of the tests had very similar vehicle responses (Tests 121 and 122) and the third test (Test 123) had relatively different vehicle responses. For Tests 121 and 122, the Speed at Maximum Roll Angle was 31.0 mph (for both tests) versus 35.4 mph for Test 123. The Peak Lateral Accelerations Prior to Maximum Roll Angle was 0.77 g for Tests 121 and 122 and was 0.71 g for Test 123. For Tests 121 and 122 the Maximum Roll Angles were 8.5 and 8.3 degrees respectively while Test 123 had a Maximum Roll Angle of 7.9 degrees.

The handwheel angle, vehicle speed, lateral acceleration, and roll angle traces for Tests 121 and 122 are given in Figures 7.2 and 7.3. The traces were adjusted in time so the initiation of the steering input occurs at approximately the same time for both tests. The handwheel angle and vehicle speed traces shown in Figure 7.2 are nearly identical for the two tests.

The lateral acceleration and roll angle traces shown in Figure 7.3 are very similar for the two tests except that Test 122 has vehicle responses that occur slightly later than they do for Test 121. After the first oscillation, the traces for Test 122 appear to lag those for Test 121 by approximately the same amount for each oscillation.

The handwheel angle, vehicle speed, lateral acceleration, and roll angle traces for Tests 121 and 123 are given in Figures 7.4 and 7.5. The traces were adjusted in time so the completion of the steering input occurs at approximately the same time for both tests (approximately 1.1 seconds). The handwheel input for Test 123 occurs over a greater period of time (slower handwheel rate) than that for Test 121. The vehicle speed trace for Test 123 is fairly similar to Test 121 at the beginning of the tests, but the speed for Test 123 is higher as the tests proceed. This suggests that the driver applied greater throttle in Test 123 than he did in Test 121. The driver had been instructed to maintain the throttle for these tests. Throttle position was not measured so it is not clear if the driver released the throttle in Test 121 (and 122), pressed further on the gas pedal (more than just maintaining throttle) in Test 123, or some combination of the two.

The lateral acceleration and roll angle traces (shown in Figure 7.5) for Test 123 are fairly similar to those for Test 121 at the beginning of the traces, but are more damped as the traces continue. This suggests that the difference in handwheel rates for the two tests plays much less of a role in the differences between the vehicle responses than does the greater throttle application. The frequency of oscillation for the two tests is fairly similar at the beginning, but the frequency of oscillation for Test 123 is greater later in the test. The peak responses occur on the third oscillation for Test 123. They occur on the fourth oscillation for Test 121.

As seen in Table 7.1, Tests 179 and 180 for Driver C have speeds that are slightly below and slightly above (respectively) those for Tests 121 through 123 for Driver A. The Peak Lateral Acceleration Prior to Maximum Roll Angles ranged from 0.66 to 0.67 g for Tests 179 and 180 versus 0.71 to 0.77 g for Tests 121 through 123. The Maximum Roll Angle ranged from 7.0 to 7.1 degrees versus 7.9 to 8.5 degrees.

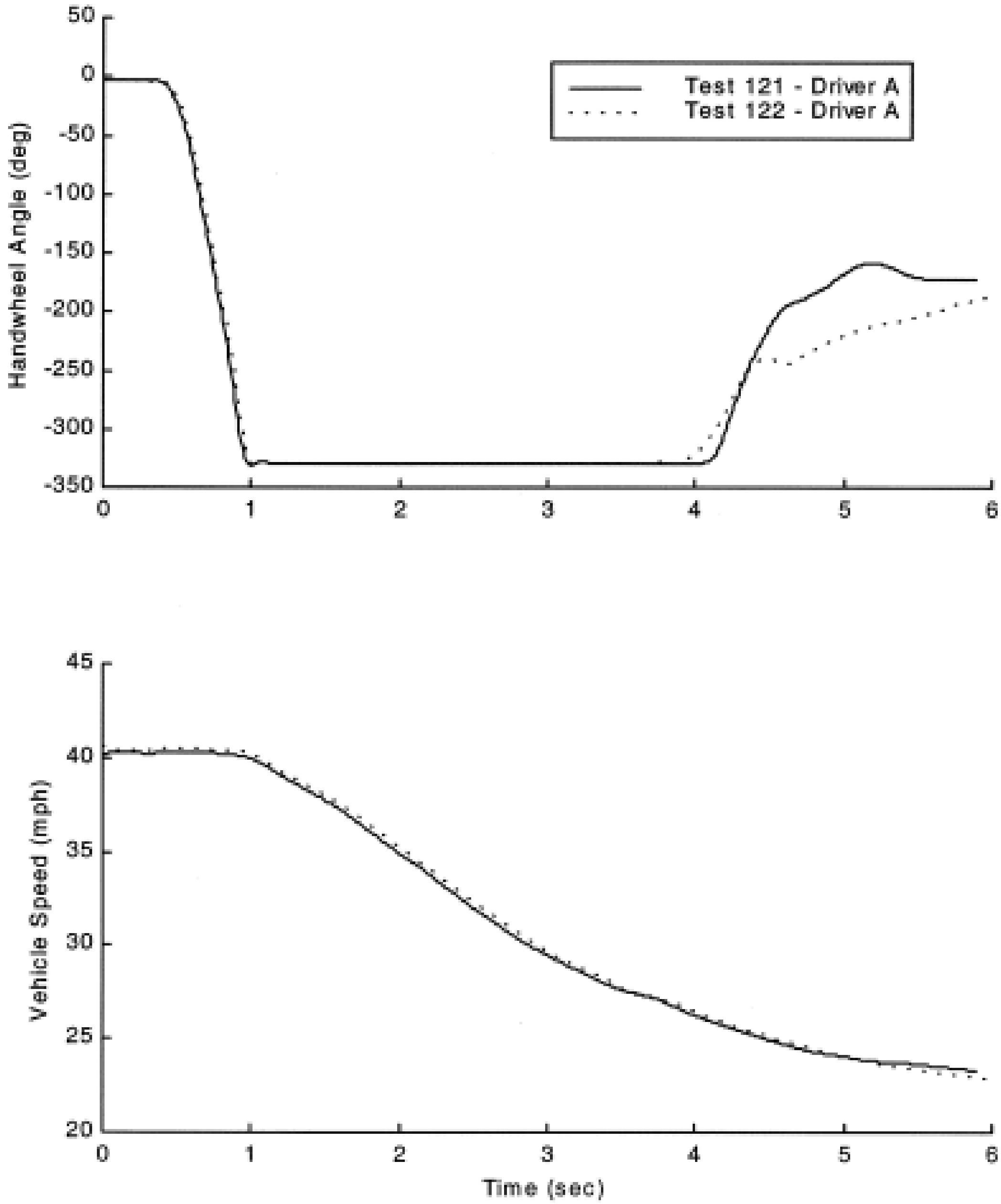


Figure 7.2 -- Handwheel Angle and Vehicle Speed Traces for Two Similar Vehicle Speed Trace Tests - Driver A

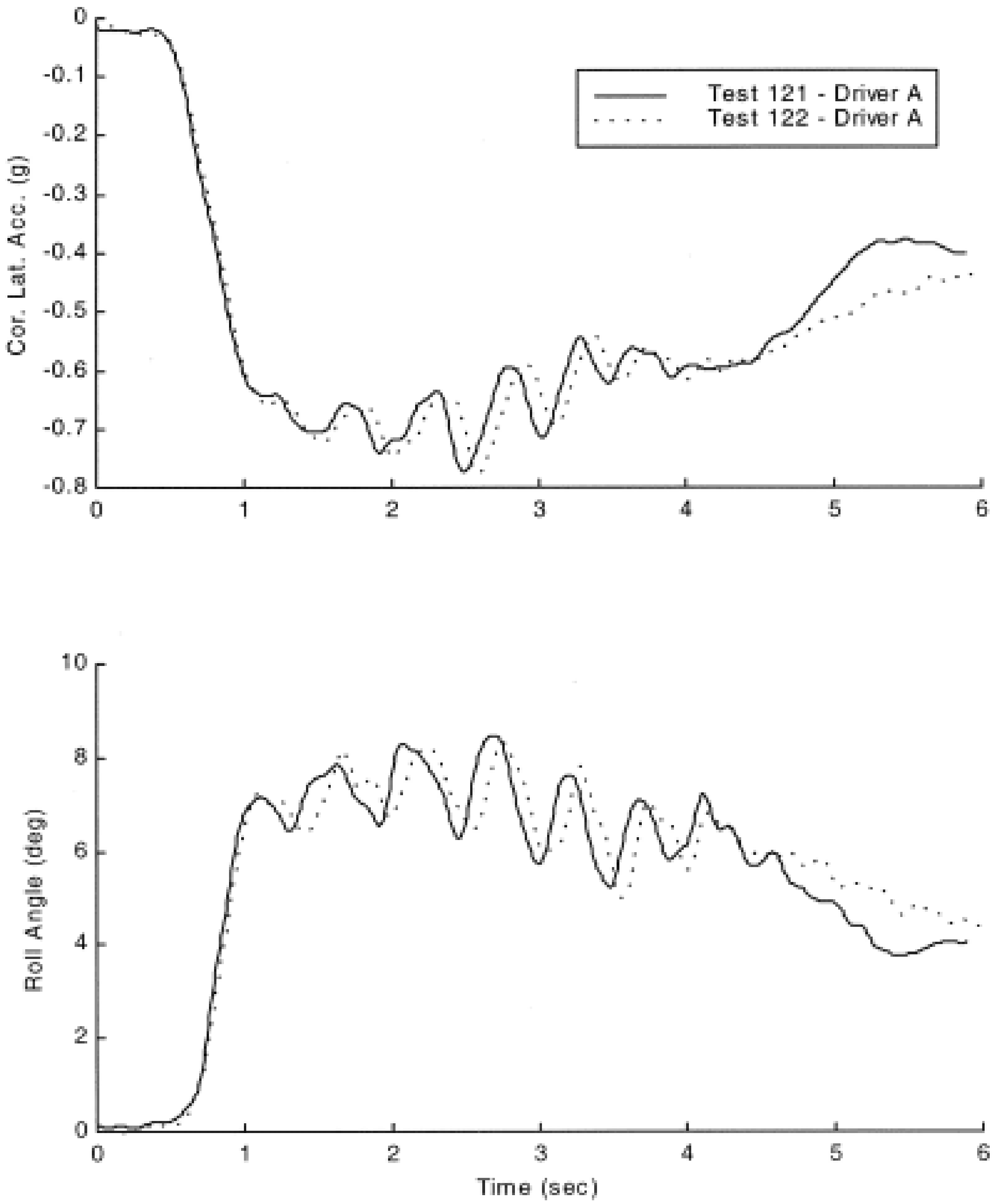


Figure 7.3 -- Corrected Lateral Acceleration and Roll Angle Traces for Two Similar Vehicle Speed Trace Tests - Driver A

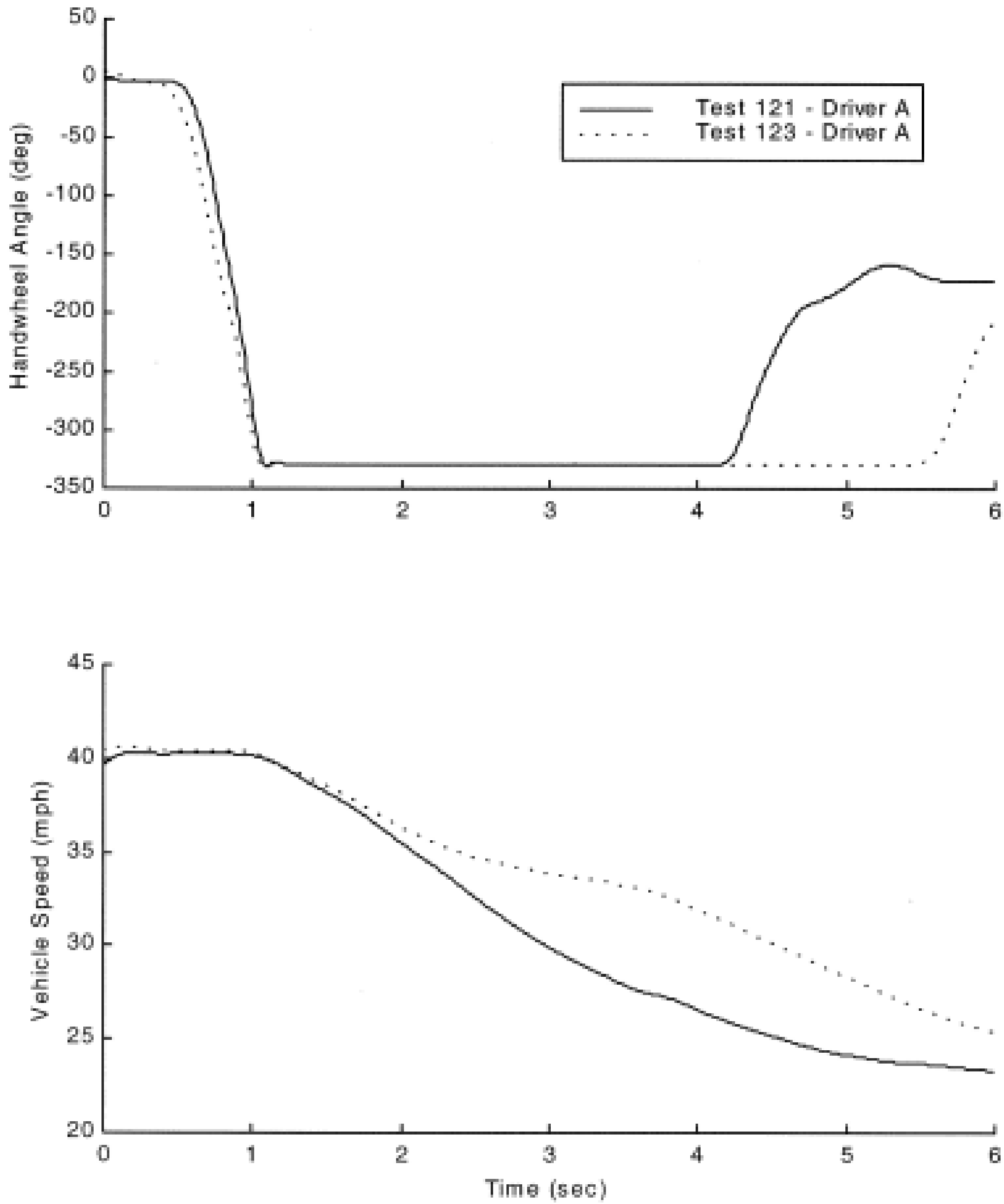


Figure 7.4 -- Handwheel Angle and Vehicle Speed Traces for Two Dissimilar Vehicle Speed Trace Tests - Driver A

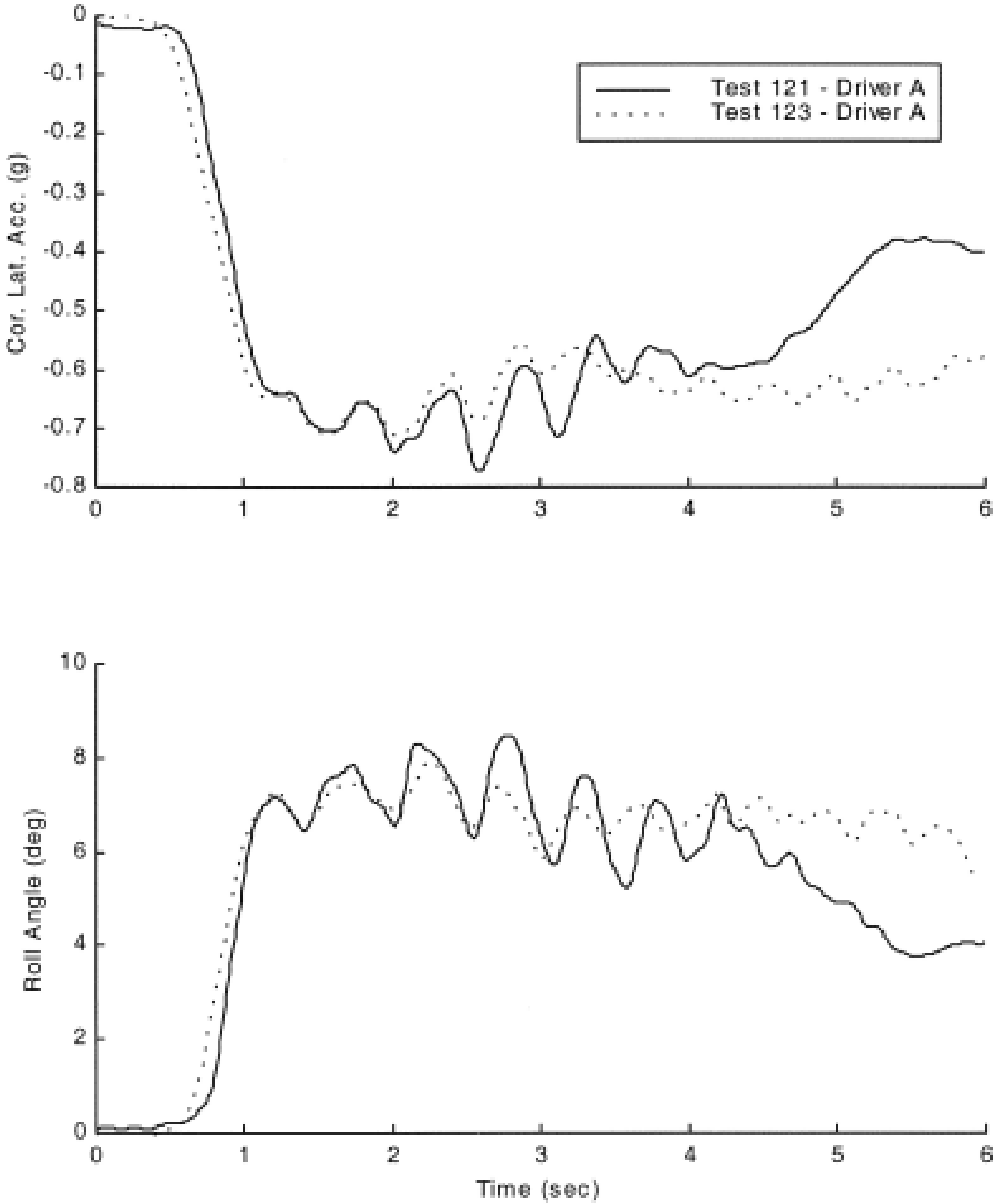


Figure 7.5 -- Corrected Lateral Acceleration and Roll Angle Traces for Two Dissimilar Vehicle Speed Trace Tests - Driver A

The handwheel angle, vehicle speed, lateral acceleration, and roll angle traces for Tests 179 and 180 are given in Figures 7.6 and 7.7. The traces were adjusted in time so the initiation of the steering input occurs at approximately the same time for both tests. The handwheel angle traces shown in Figure 7.6 are nearly identical for the two tests. The initial speed for the two tests are different, but the driver obviously applies a greater throttle than that supplied in Tests 121 and 122. The lateral acceleration and roll angle traces are much more subdued (the oscillation magnitudes are lower) than those found in Tests 121 through 123.

Tests 121 and 180 are shown in Figures 7.8 and 7.9. The differences for a more heavily applied throttle are very apparent in these tests. Compared to Test 123 (Figure 7.4), the handwheel angle trace for Test 180 is very similar to Test 121. Test 180 is similar to Test 123 in that a greater throttle was applied compared to Test 121. These two facts further suggest that the greater throttle input (Tests 180 and 123 versus Test 121) is responsible for the more subdued response than is the slower handwheel rate (Test 123 versus Test 121).

As stated earlier, Driver C had two-wheel lift occur at higher speeds than that for Driver A. Throttle application appears to be the most probable explanation for these differences. Further testing with more highly controlled throttle would be required to determine the repeatability of the speed necessary to produce two-wheel lift.

The lateral acceleration required to produce two-wheel lift for each driver/steer direction are given in Table 7.2. The values were very similar for the two drivers in the right steer direction (0.81 g versus 0.83 g), but relatively different for the left steer direction (0.76 g versus 0.87 g).

Table 7.2 -- Minimum Corrected Lateral Acceleration Values for J-Turn Tests with Two-Wheel Lift

Driver	Right	Left
A	0.81	0.76
C	0.83	0.87

The Lateral Acceleration at Rollover (LAR) values for each driver/steer direction are given in Table 7.3. Driver A had an LAR value of 0.76 g for left steer versus 0.81 g for Driver C. The LAR for right steers were more similar (0.78 g versus 0.79 g). The calculation of an LAR is described in detail in [1]. The LAR value is normally computed for a Fishhook maneuver and requires that three instances of two-wheel lift be noted. There was only one instance of two-wheel lift for each driver/steer direction combination for these J-Turn tests. More testing would be necessary to determine if requiring more instances of two-wheel lift for each test set would narrow the range of variability in the LAR values (at least in left steer) required to produce two-wheel lift results.

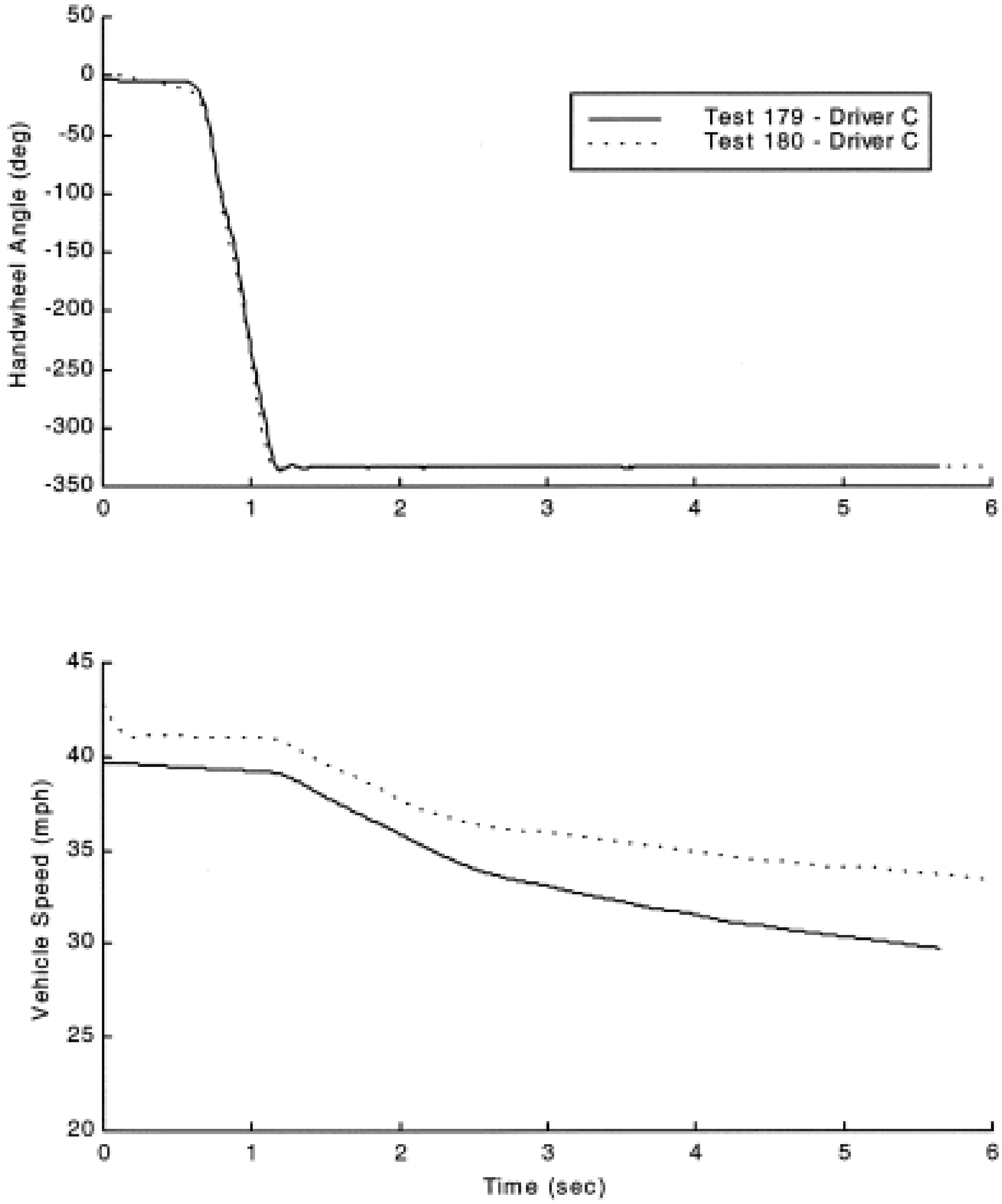


Figure 7.6 -- Handwheel Angle and Vehicle Speed Traces for Tests with Greater Throttle Input - Driver C

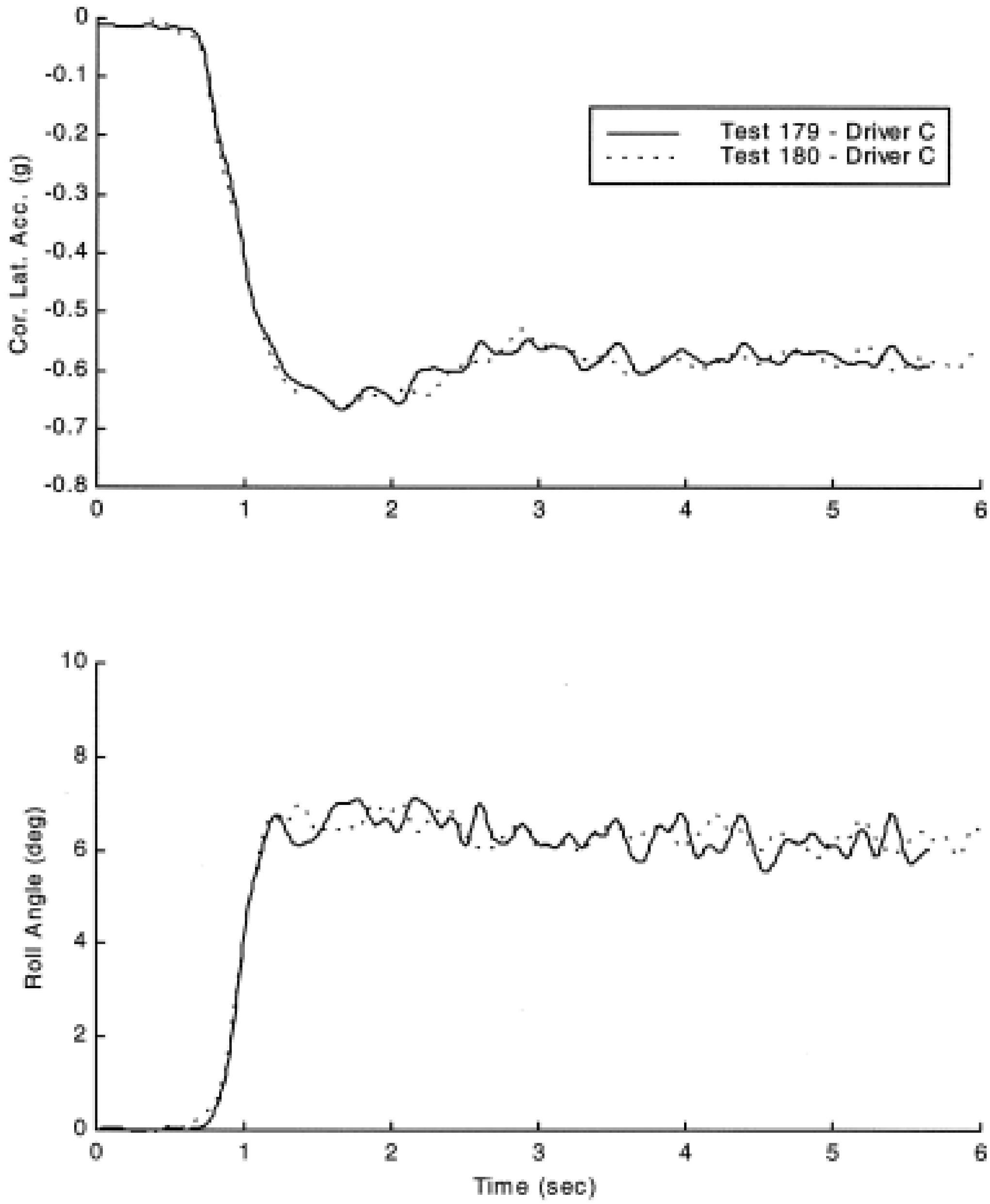


Figure 7.7 -- Corrected Lateral Acceleration and Roll Angle Traces for Tests with Greater Throttle Input - Driver C

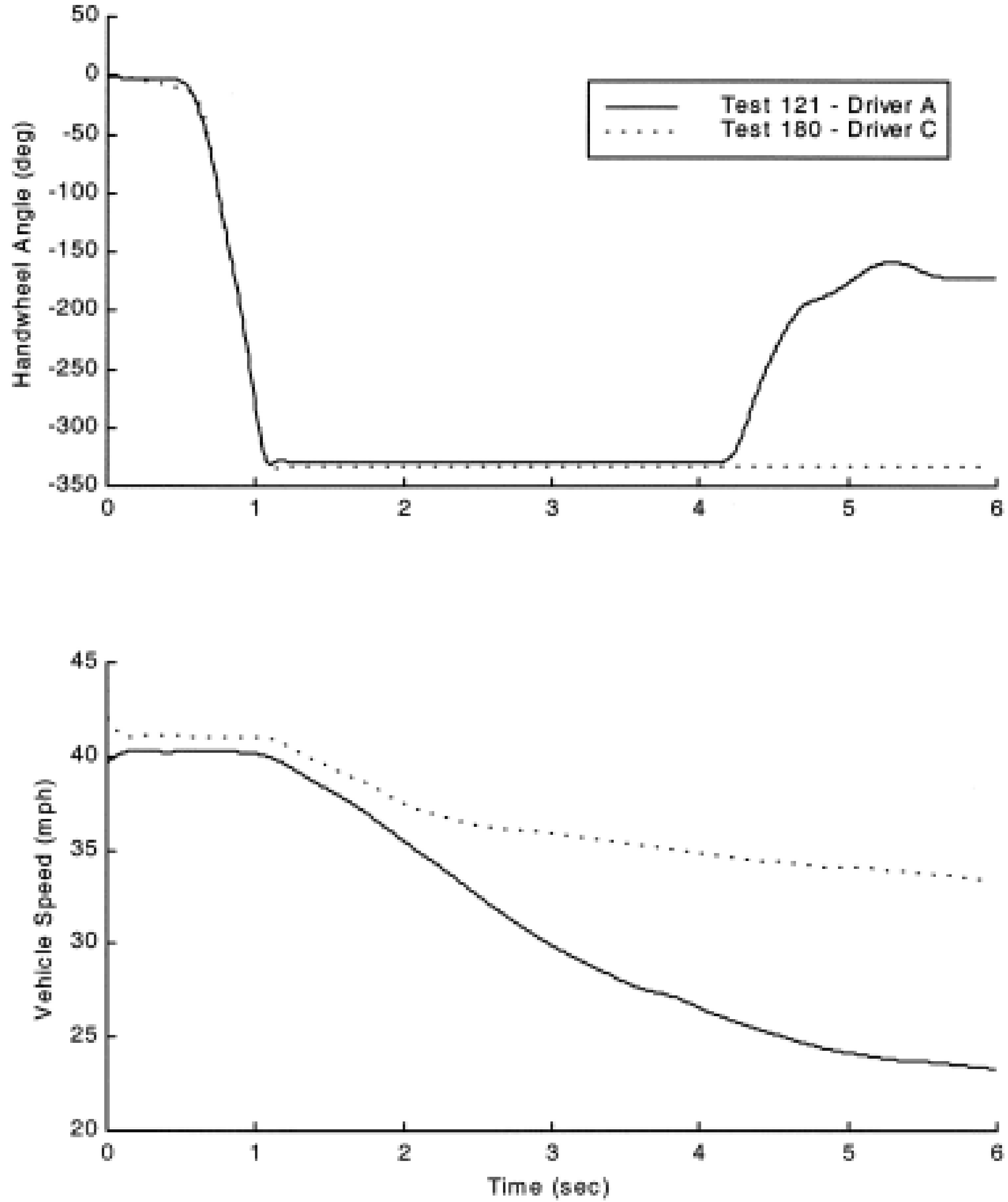


Figure 7.8 -- Handwheel Angle and Vehicle Speed Traces for Two Dissimilar Vehicle Speed Trace Tests - Drivers A and C

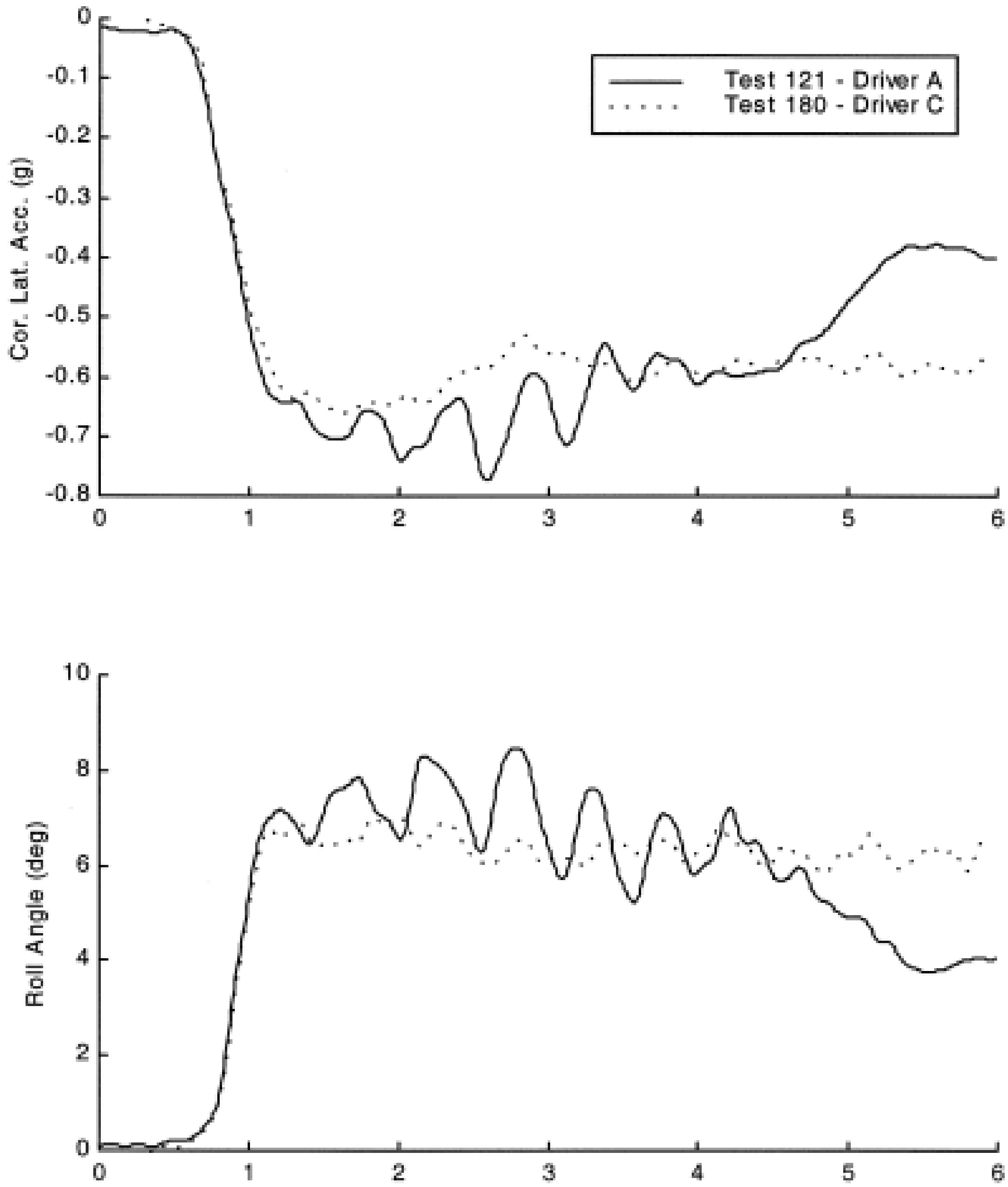


Figure 7.9 -- Corrected Lateral Acceleration and Roll Angle Traces for Two Dissimilar Vehicle Speed Trace Tests - Drivers A and C

Table 7.3 -- Lateral Acceleration at Rollover (LAR) Values for J-Turn Tests

Driver	Right	Left
A	0.78	0.76
C	0.79	0.81

The following statements were made in the Phase I-A report [1], but are worth repeating. They are generally true for all the maneuvers studied. In addition to test input variability, there is inherent non-repeatability in the tires, the vehicle components (e.g. shock absorbers, bushings, etc.), and the test surface. These effects are random in nature and little can be done to eliminate their effects on repeatability.

There are test conditions that have a non-random influence on the measured vehicle responses. For example, testing at a different ambient temperature or on a somewhat different surface could result in different measured vehicle responses. The effect of changes of this sort on the overall outcome of a test regarding the limits of vehicle response, i.e., whether the test would result in two-wheel lift, spin out, or plow out, is not known.

7.1.4 J-Turn Testing Problems

For two of the J-Turn tests, the drivers had some problems with the steering stop. In Test 119, the driver overshot the steering stop. In Test 187, the handwheel hit the steering stop, came off the steering stop, and then was turned back into the steering stop. In Phase II testing a steering controller will be used to apply the steering input and should keep these types of problems from occurring in future testing.

As described in Section 7.3, the drivers had a difficult time applying a constant throttle during testing. It appears there were instances when they have may have released throttle and/or increased throttle. It also appears that increasing the throttle tends to make the vehicle more stable (at least at lower speeds) by reducing the amount of roll oscillation. To reduce the amount of variability in testing, the drivers will release the throttle in Phase II research upon the initiation of the steering input.

7.1.5 Summary of Driver Controlled J-Turn Results

In general, increasing J-Turn severity, by increasing steering magnitude or vehicle speed, resulted in increasing lateral acceleration and roll angle up to the point of limit response.

For the Toyota 4Runner, the limit response during the J-Turn testing was two-wheel lift. Both drivers were able to produce two-wheel lift in both the Left and Right steer directions. In Phase I-A, the two-wheel lifts did not occur until after the 4Runner's tires had significant wear. In this phase of testing (Phase I-B) two-wheel lift was achieved with only slight tire wear (at least in the Right steer direction).

The J-Turn maneuver was found to be fairly repeatable. For all groups of repeatability tests (similar speed, handwheel inputs, and throttle), the resulting maximum lateral accelerations and maximum roll angles were very similar. Throttle position did appear to make a large difference in test results. To reduce the amount of variability in testing, the drivers will release the throttle in Phase II research upon the initiation of the steering input.

The J-Turn maneuver is a simple test to conduct relative to other vehicle rollover propensity tests. It induces two-wheel lift for some vehicles. The initial test speed appears to be a measure that can be used to quantify a vehicle's rollover propensity. For the above reasons, the J-Turn maneuver is a good candidate for use in a potential dynamic rollover propensity test procedure.

7.2 J-Turn with Pulse Braking Maneuver Test Results and Analysis - Driver Effects

A limited number of J-Turn with Pulse Braking tests were performed by two drivers. The results from these tests are presented below. Driver effects are examined and a general assessment of the J-Turn with Pulse Braking maneuver is given.

7.2.1 J-Turn With Pulse Braking Tests Performed for Each Vehicle

Two drivers conducted a limited number of J-Turn with Pulse Braking tests with the 1984 Ford Bronco II. A set of example plots for J-Turn with Pulse Braking results are given in Figures 7.10 through 7.17. The handwheel angle is given in Figure 7.10 and shows that the driver turns the handwheel as fast as possible to a steering stop and then maintains the set angle until the maneuver is complete. Figure 7.11 shows the handwheel rate with a peak rate of approximately 800 deg/sec.

The driver-applied, short-duration brake pulse is shown in Figure 7.12. The longitudinal acceleration of the vehicle is shown in Figure 7.13. The initial deceleration is due to the large handwheel angle and the driver releasing the throttle, while the large peak is due to brake pulse.

The vehicle roll angle is shown in Figure 7.14. The roll angle has an initial peak prior to the pulse brake, then a "dip" due to the pulse brake application, and after the pulse the roll angle achieves a higher value than pre-pulse. As shown in Figure 7.15, the lateral acceleration decreases fairly dramatically when the pulse brake is applied due to a loss of side-force capability because the tire is using a lot of its possible adhesion for braking. This loss of side-force causes the dip in the roll angle seen in Figure 7.15. As seen in Figure 7.14, the peak lateral acceleration after the brake pulse can be greater than that seen before the pulse.

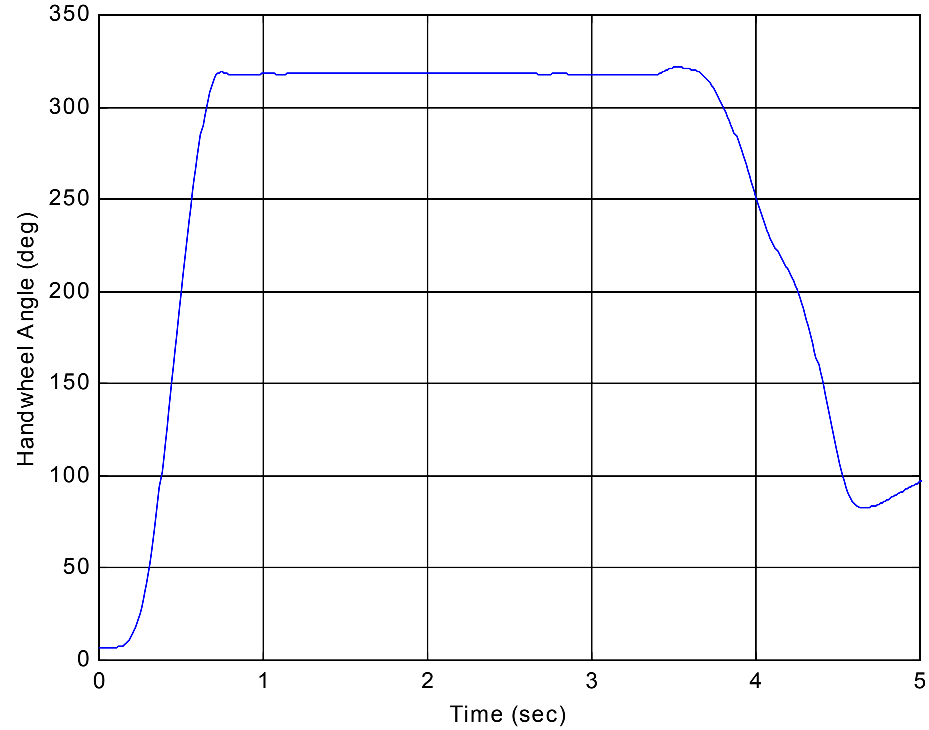


Figure 7.10 -- Handwheel Angle Versus Time for Bronco II Test No. 280

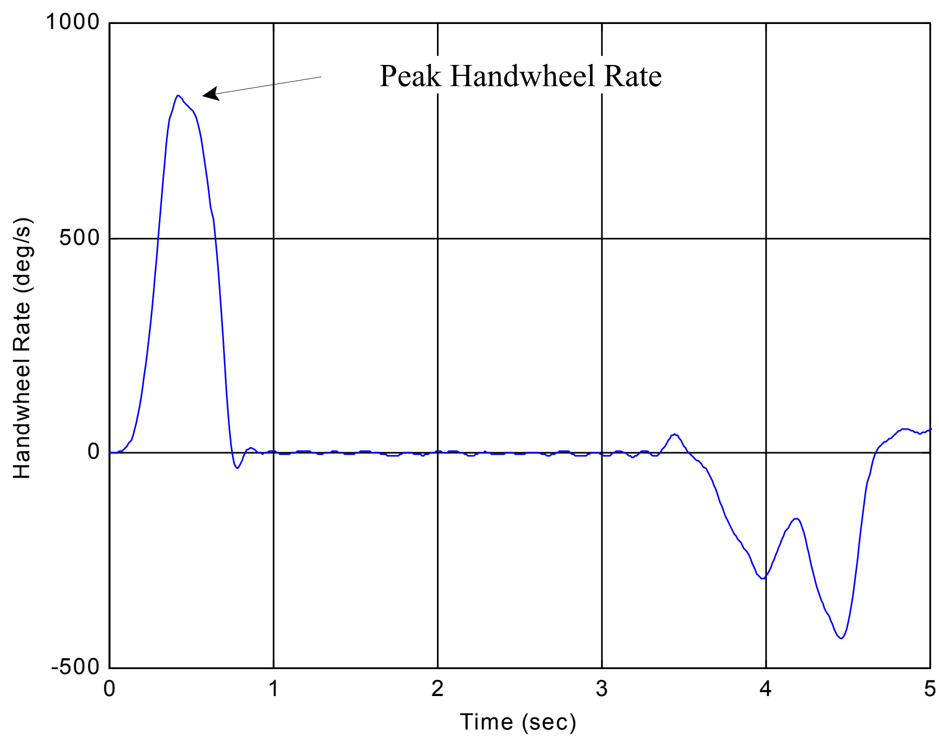


Figure 7.11 -- Handwheel Rate Versus Time for Bronco II Test No. 280

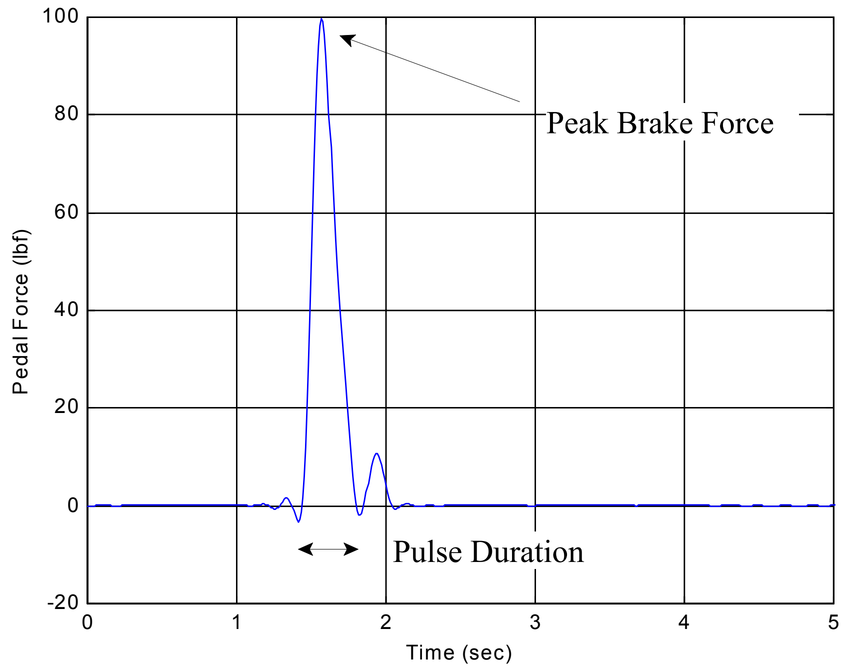


Figure 7.12 -- Pedal Force Versus Time for Bronco II Test No. 280

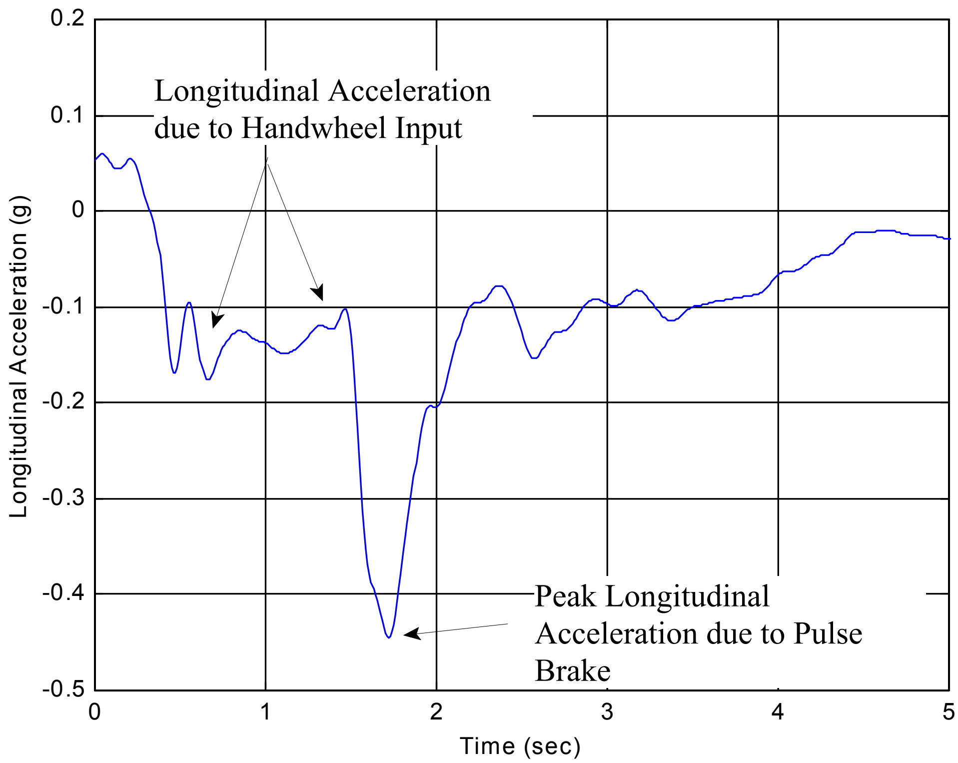


Figure 7.13 -- Longitudinal Acceleration Versus Time for Bronco II Test No. 280

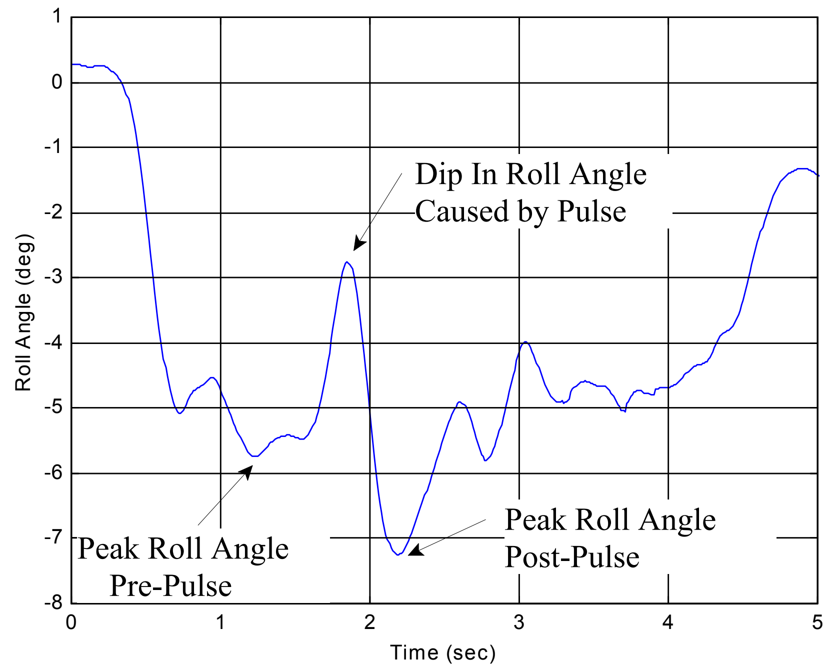


Figure 7.14 -- Roll Angle Versus Time for Bronco II Test No. 280

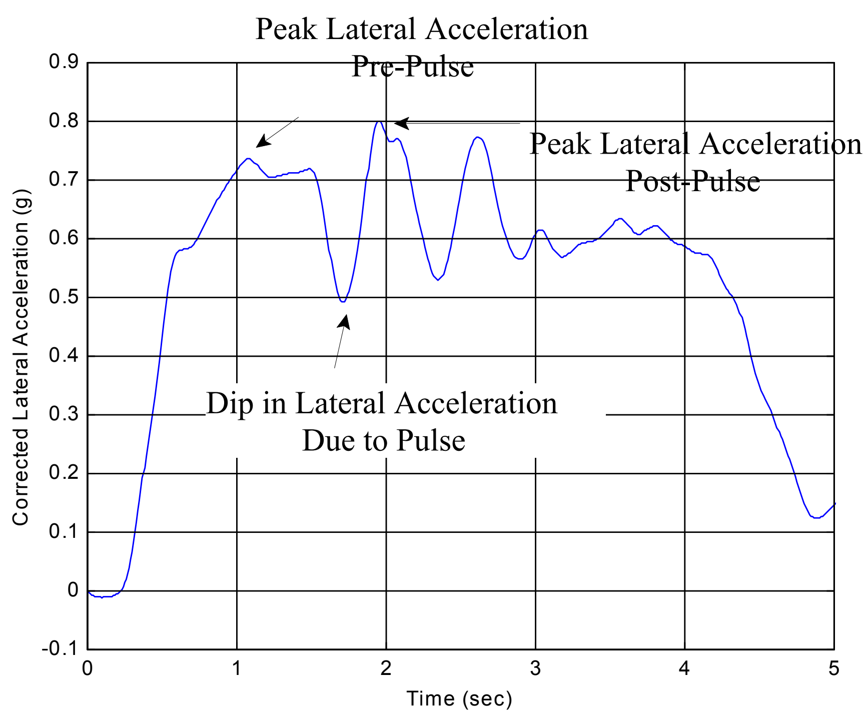


Figure 7.15 -- Corrected Lateral Acceleration Versus Time for Bronco II Test No. 280

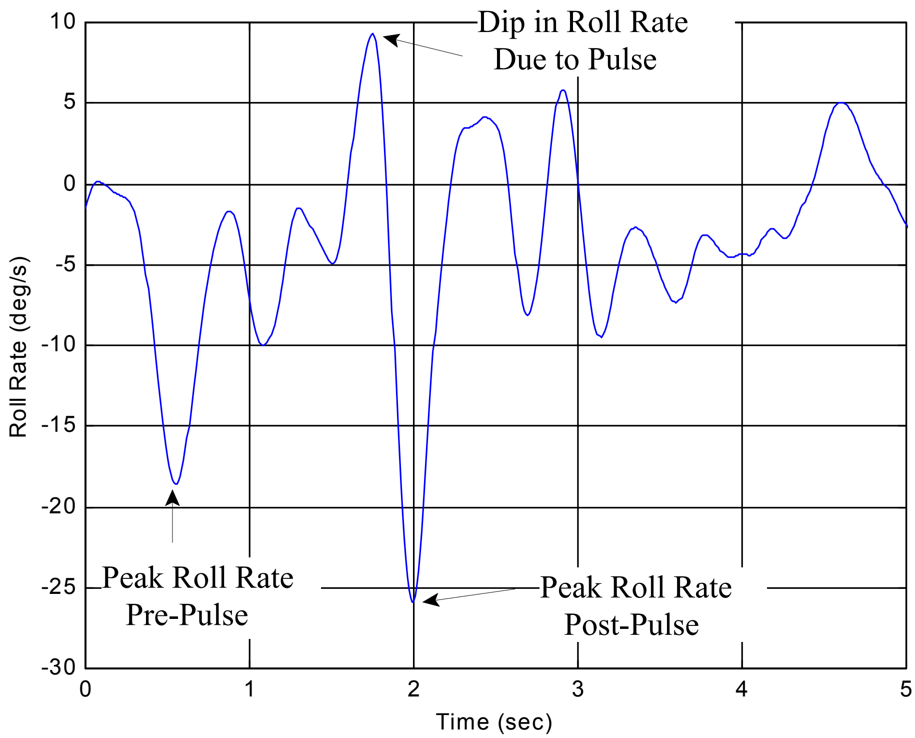


Figure 7.16 -- Roll Rate Versus Time for Bronco II Test No. 280

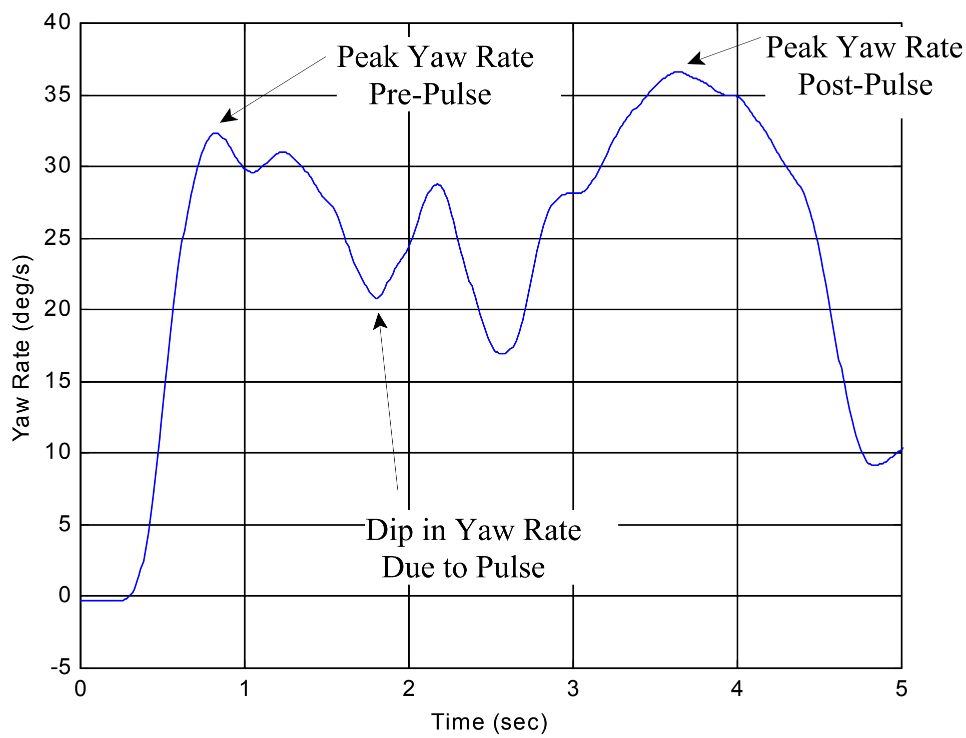


Figure 7.17 -- Yaw Rate Versus Time for Bronco II Test No. 280

The roll rate is plotted in Figure 7.16. There is an initial negative peak before the brake pulse followed by a second negative peak of lesser magnitude. If the brake pulse were not applied, decreasing smaller peaks would occur. There is a positive peak caused by the brake pulse followed by a relatively large negative peak. This large negative peak is greater than the initial negative peak caused by the initial steer. The brake pulse causes a large side-to-side momentum swing which is one of the main reasons the vehicle has a larger roll angle after the pulse than it did before the pulse. As seen in Figure 7.17, the brake pulse causes some oscillations in the yaw rate vehicle response. For a J-Turn test (without Pulse Braking), the yaw rate response is relatively flat after the initial peak. The brake pulse causes a decrease in the turning capability and this disturbance causes the vehicle to have an oscillatory response in yaw.

Driver A completed two sets of tests for each steering direction while Driver C completed one set. Tests results are given in Tables 7.4 through 7.6.

Table 7.4 lists the Initial Speed, Handwheel Angle, Peak Handwheel Rate, Pulse Brake Magnitude, Pulse Brake Duration, Deceleration due to Turn (deceleration due to the large handwheel input prior to the brake pulse), and Deceleration due to Turn and Brake (the peak deceleration that occurs during the brake pulse). Average values for each driver set are also given. The driver set consists of the left and right turn tests conducted on one set of tires. The averages were calculated using the absolute value of the measured parameters.

The Peak and “Dip” Roll Angle and Corrected Lateral Acceleration values are given in Table 7.5. The Amount of Two-Wheel Lift is also listed. The Peak and “Dip” Roll Rate and Yaw Rate values are given in Table 7.6. The Test Number, Initial Speed, Handwheel Angle, and Pulse Brake Magnitude are repeated in Tables 7.5 and 7.6.

Table 7.4 -- Driver Controlled J-Turn with Pulse Brake Results - Handwheel Rate, Pulse Brake, and Deceleration Values

Driver	Test No.	Initial Speed	Hand-wheel Angle	Peak Handwheel Rate	Pulse Brake Magnitude	Pulse Brake Duration	Decel due to Turn	Decel due to Turn & Brake
A	279	35.4	317	788	155	0.37	-0.12	-0.58
	280	38.7	318	831	100	0.35	-0.14	-0.45
	281	38.5	318	888	176	0.37	-0.13	-0.63
	282	36.3	317	877	187	0.34	-0.13	-0.61
	283	36.5	319	837	142	0.32	-0.13	-0.52
	284	38.6	318	945	175	0.37	-0.13	-0.63
	285	35.3	-329	-896	171	0.45	-0.17	-0.71
	286	36.7	-328	-829	161	0.34	-0.17	-0.64
	287	37.9	-328	-889	173	0.36	-0.17	-0.66
	288	39.7	-330	-899	138	0.33	-0.17	-0.60
	289	40.0	-329	-855	122	0.45	-0.18	-0.65
	290	40.4	-329	-719	174	0.35	-0.18	-0.64
	291	42.0	-328	-815	121	0.36	-0.18	-0.61
	293	45.1	-329	-753	185	0.47	-0.13	-0.72
	294	44.7	-329	-871	196	0.40	-0.18	-0.69
	295	44.6	-329	-854	166	0.50	-0.18	-0.78
	296	42.9	-329	-774	169	0.39	-0.18	-0.69
	297	43.7	-329	-883	191	0.42	-0.18	-0.73
			Average	845	161	0.39	0.16	0.64
A	303	34.9	-330	-856	159	0.36	-0.19	-0.68
	304	36.2	-330	-904	161	0.42	-0.19	-0.70
	305	38.8	-329	-889	171	0.30	-0.19	-0.61
	306	39.8	-331	-904	165	0.38	-0.19	-0.65
	307	39.4	-331	-900	175	0.33	-0.19	-0.65
	308	39.7	-330	-917	172	0.39	-0.20	-0.67
	309	39.0	-330	-888	151	0.39	-0.19	-0.69
	310	35.4	-330	-818	157	0.36	-0.19	-0.65
	311	38.4	-330	-931	190	0.35	-0.19	-0.65
	312	36.5	337	847	144	0.30	-0.13	-0.52
	313	37.8	338	884	193	0.33	-0.14	-0.65
	314	39.2	333	967	145	0.31	-0.15	-0.55
	315	39.3	338	916	170	0.27	-0.13	-0.51
	316	40.6	338	1006	161	0.28	-0.15	-0.54
	317	41.5	339	909	162	0.30	-0.15	-0.54
	318	42.0	340	913	194	0.33	-0.14	-0.62
	319	40.5	340	943	192	0.32	-0.14	-0.59
	321	40.1	340	914	186	0.33	-0.14	-0.62
			Average	906	169	0.34	0.17	0.62

Driver	Test No.	Initial Speed	Hand-wheel Angle	Peak Handwheel Rate	Pulse Brake Magnitude	Pulse Brake Duration	Decel due to Turn	Decel due to Turn & Brake
C	326	35.9	329	885	221	0.39	-0.08	-0.74
	327	36.8	330	865	254	0.36	-0.10	-0.75
	328	38.9	331	924	264	0.49	-0.09	-0.78
	329	38.0	331	924	263	0.47	-0.08	-0.80
	330	37.0	330	782	255	0.44	-0.08	-0.75
	331	36.3	330	690	250	0.37	-0.07	-0.69
	332	35.2	330	850	235	0.34	-0.06	-0.68
	333	35.9	-324	-904	260	0.50	-0.12	-0.80
	334	37.0	-326	-641	229	0.47	-0.10	-0.72
	335	38.3	-327	-888	209	0.37	-0.10	-0.71
	336	39.9	-328	-755	200	0.45	-0.10	-0.74
	337	39.4	-329	-663	255	0.49	-0.13	-0.80
	338	39.3	-329	-949	253	0.52	-0.15	-0.78
	339	40.8	-329	-912	257	0.46	-0.12	-0.75
	340	41.9	-328	-832	227	0.48	-0.13	-0.78
	341	43.7	-327	-748	256	0.50	-0.13	-0.80
	342	42.6	-328	-864	256	0.53	-0.13	-0.81
			Average	828	244	0.45	0.10	0.76

Table 7.5 -- Driver Controlled J-Turn with Pulse Brake Results - Roll Angle, Two-Wheel Lift, and Corrected Lateral Acceleration Values

Driver	Test No.	Initial Speed	Handwheel Angle	Pulse Brake Magnitude	Peak Roll Angle Pre-Pulse	Roll Angle Dip due to Pulse	Peak Roll Angle Post-Pulse	Amount of Two-Wheel Lift	Peak Cor. Lat. Acc. Pre-Pulse	Cor. Lat. Acc. Dip due to Pulse	Peak Cor. Lat. Acc. Post-Pulse
A	279	35.4	317	155	-5.3	-1.5	-7.9	None	0.72	0.39	0.79
	280	38.7	318	100	-5.8	-2.8	-7.3	None	0.74	0.49	0.80
	281	38.5	318	176	-5.7	0.0	-9.8	Minor	0.74	0.25	0.94
	282	36.3	317	187	-5.6	0.0	-10.5	Minor	0.73	0.26	0.93
	283	36.5	319	142	-5.6	-2.4	-7.5	None	0.74	0.48	0.78
	284	38.6	318	175	-5.5	0.2	-10.6	Minor	0.74	0.25	0.92
	285	35.3	-329	171	5.2	0.2	8.6	None	-0.70	-0.17	-0.72
	286	36.7	-328	161	5.6	1.1	9.0	None	-0.68	-0.26	-0.75
	287	37.9	-328	173	5.7	0.8	5.9	None	-0.69	-0.25	-0.79
	288	39.7	-330	138	5.8	1.4	9.8	None	-0.70	-0.36	-0.77
	289	40.0	-329	122	5.9	0.9	9.0	None	-0.70	-0.24	-0.74
	290	40.4	-329	174	5.8	1.2	10.0	None	-0.71	-0.23	-0.77
	291	42.0	-328	121	5.9	1.8	9.9	Minor	-0.70	-0.34	-0.82
	293	45.1	-329	185	5.7	-1.3	9.2	None	-0.73	-0.16	-0.79
	294	44.7	-329	196	6.1	-1.5	11.7	Minor	-0.73	-0.20	-0.91
	295	44.6	-329	166	6.2	0.1	12.4	Moderate	-0.75	-0.19	-0.86
	296	42.9	-329	169	6.4	0.8	10.2	None	-0.73	-0.22	-0.83
	297	43.7	-329	191	6.3	0.1	11.1	Minor	-0.72	-0.22	-0.90
A	303	34.9	-330	159	5.3	0.7	8.0	None	-0.69	-0.25	-0.71
	304	36.2	-330	161	5.4	0.1	9.7	None	-0.69	-0.17	-0.77
	305	38.8	-329	171	5.6	1.7	8.9	None	-0.72	-0.34	-0.77
	306	39.8	-331	165	6.0	0.2	11.8	Minor	-0.72	-0.22	-0.95
	307	39.4	-331	175	5.5	1.0	10.0	Minor	-0.71	-0.27	-0.87
	308	39.7	-330	172	5.8	0.1	11.5	Minor	-0.72	-0.18	-0.92
	309	39.0	-330	151	5.9	0.5	10.2	Minor	-0.73	-0.23	-0.91
	310	35.4	-330	157	5.7	1.2	8.7	None	-0.72	-0.29	-0.77
	311	38.4	-330	190	6.0	0.3	10.8	Minor	-0.71	-0.21	-0.91
	312	36.5	337	144	-5.2	-1.7	-6.9	None	0.72	0.36	0.80
	313	37.8	338	193	-5.6	0.0	-9.1	None	0.72	0.22	0.90
	314	39.2	333	145	-5.9	-1.6	-8.3	None	0.73	0.36	0.82
	315	39.3	338	170	-5.8	-2.0	-8.5	None	0.74	0.43	0.81
	316	40.6	338	161	-6.4	-1.8	-9.2	Minor	0.72	0.36	0.84
	317	41.5	339	162	-6.2	-1.7	-9.4	Minor	0.75	0.35	0.83
	318	42.0	340	194	-6.4	0.2	-13.4	Major	0.77	0.26	0.97

Driver	Test No.	Initial Speed	Handwheel Angle	Pulse Brake Magnitude	Peak Roll Angle Pre-Pulse	Roll Angle Dip due to Pulse	Peak Roll Angle Post-Pulse	Amount of Two-Wheel Lift	Peak Cor. Lat. Acc. Pre-Pulse	Cor. Lat. Acc. Dip due to Pulse	Peak Cor. Lat. Acc. Post-Pulse
	319	40.5	340	192	-6.1	-0.2	-11.2	Moderate	0.75	0.24	0.96
	321	40.1	340	186	-6.7	-0.7	-10.7	Minor	0.74	0.29	0.90

Driver	Test No.	Initial Speed	Handwheel Angle	Pulse Brake Magnitude	Peak Roll Angle Pre-Pulse	Roll Angle Dip due to Pulse	Peak Roll Angle Post-Pulse	Amount of Two-Wheel Lift	Peak Cor. Lat. Acc. Pre-Pulse	Cor. Lat. Acc. Dip due to Pulse	Peak Cor. Lat. Acc. Post-Pulse
C	326	35.9	329	221	-5.2	0.8	-9.6	Minor	0.68	0.09	0.87
	327	36.8	330	254	-5.3	1.1	-10.3	Minor	0.69	0.11	0.91
	328	38.9	331	264	-5.7	2.0	-11.3	Minor	0.72	0.10	0.91
	329	38.0	331	263	-5.5	1.4	-11.2	Minor	0.70	0.09	0.95
	330	37.0	330	255	-5.3	0.9	-10.8	Minor	0.69	0.09	0.89
	331	36.3	330	250	-5.3	0.7	-10.2	Minor	0.70	0.13	0.93
	332	35.2	330	235	-5.5	1.5	-10.0	Minor	0.70	0.12	0.91
	333	35.9	-324	260	4.9	-0.6	8.6	None	-0.67	-0.06	-0.77
	334	37.0	-326	229	4.9	-0.3	8.2	None	-0.66	-0.16	-0.76
	335	38.3	-327	209	5.0	-0.7	9.3	None	-0.68	-0.15	-0.78
	336	39.9	-328	200	5.7	-0.6	9.9	None	-0.67	-0.14	-0.83
	337	39.4	-329	255	5.1	-0.6	10.3	Minor	-0.68	-0.09	-0.87
	338	39.3	-329	253	5.7	-0.8	10.8	Minor	-0.68	-0.10	-1.02
	339	40.8	-329	257	5.5	-0.5	10.8	Minor	-0.71	-0.12	-0.98
	340	41.9	-328	227	5.2	-0.8	10.5	Minor	-0.70	-0.15	-1.01
	341	43.7	-327	256	5.8	-0.3	11.3	Minor	-0.69	-0.09	-1.05
	342	42.6	-328	256	5.1	-0.6	11.1	Minor	-0.69	-0.09	-1.00

Table 7.6: Driver Controlled J-Turn with Pulse Brake Results - Roll Rate and Yaw Rate Values

Driver	Test No.	Initial Speed	Hand-wheel Angle	Pulse Brake Magnitude	Peak Roll Rate Pre-Pulse	Roll Rate Dip due to Pulse	Peak Roll Rate, Post Pulse	Peak Yaw Rate Pre-Pulse	Yaw Rate Dip due to Pulse	Peak Yaw Rate Post-Pulse
A	279	35.4	317	155	-16.6	16.4	-34.7	32.4	16.9	36.3
	280	38.7	318	100	-18.6	9.3	-25.9	32.3	20.8	36.6
	281	38.5	318	176	-17.3	23.1	-52.0	32.2	12.8	35.9
	282	36.3	317	187	-15.9	23.4	-52.0	31.6	12.8	35.5
	283	36.5	319	142	-17.5	10.3	-26.6	31.6	22.1	34.0
	284	38.6	318	175	-17.9	23.4	-50.8	31.5	14.7	34.9
	285	35.3	-329	171	16.0	-20.5	43.1	-32.0	-7.5	-41.8
	286	36.7	-328	161	15.7	-21.0	42.8	-32.1	-12.1	-37.5
	287	37.9	-328	173	17.1	-22.7	46.2	-32.3	-11.8	-34.5
	288	39.7	-330	138	17.0	-19.0	37.5	-31.0	-16.7	-36.2
	289	40.0	-329	122	14.0	-19.9	40.6	-30.1	-9.1	-37.1
	290	40.4	-329	174	14.2	-21.2	43.8	-30.9	-10.4	-35.3
	291	42.0	-328	121	17.2	-16.4	38.0	-31.2	-15.4	-35.7
	293	45.1	-329	185	14.0	-21.2	43.2	-27.5	-1.2	-35.6
	294	44.7	-329	196	18.3	-24.5	51.2	-30.9	-9.4	-37.2
	295	44.6	-329	166	17.8	-25.4	45.9	-31.9	-7.6	-35.8
	296	42.9	-329	169	13.0	-19.4	43.1	-31.2	-7.2	-35.8
	297	43.7	-329	191	14.3	-21.0	46.2	-31.7	-5.8	-35.6
A	303	34.9	-330	159	14.8	-18.7	40.0	-31.8	-12.5	-40.8
	304	36.2	-330	161	16.2	-19.8	47.7	-31.9	-10.2	-40.1
	305	38.8	-329	171	16.1	-18.4	38.5	-31.7	-16.4	-36.2
	306	39.8	-331	165	16.8	-24.1	51.8	-32.5	-13.1	-37.1
	307	39.4	-331	175	16.1	-21.0	44.3	-31.0	-14.8	-37.4
	308	39.7	-330	172	17.0	-24.6	51.6	-32.1	-12.8	-37.1
	309	39.0	-330	151	15.1	-21.4	48.7	-32.9	-13.5	-37.8
	310	35.4	-330	157	14.2	-18.0	41.2	-32.5	-16.6	-38.0
	311	38.4	-330	190	16.3	-26.1	52.0	-32.9	-13.4	-37.4
	312	36.5	337	144	-16.5	14.5	-31.2	31.4	14.1	37.7
	313	37.8	338	193	-17.7	24.2	-50.0	31.5	9.3	41.6
	314	39.2	333	145	-18.4	14.8	-34.2	29.1	15.6	36.0
	315	39.3	338	170	-17.8	15.7	-31.5	32.1	20.7	35.6
	316	40.6	338	161	-19.7	17.5	-36.3	28.9	18.8	35.2
	317	41.5	339	162	-17.0	15.3	-35.6	31.6	15.7	36.4
	318	42.0	340	194	-19.4	24.9	-52.1	32.3	11.1	37.4
	319	40.5	340	192	-17.0	23.4	-52.3	31.6	11.0	37.6

Driver	Test No.	Initial Speed	Hand-wheel Angle	Pulse Brake Magnitude	Peak Roll Rate Pre-Pulse	Roll Rate Dip due to Pulse	Peak Roll Rate, Post Pulse	Peak Yaw Rate Pre-Pulse	Yaw Rate Dip due to Pulse	Peak Yaw Rate Post-Pulse
	321	40.1	340	186	-17.7	18.7	-46.2	32.3	10.4	36.4
C	326	35.9	329	221	-18.2	23.2	-52.9	30.4	11.9	40.7
	327	36.8	330	254	-18.6	26.1	-53.3	30.7	12.5	38.3
	328	38.9	331	264	-18.9	31.9	-48.2	30.6	12.9	37.7
	329	38.0	331	263	-17.8	30.0	-49.4	30.6	12.9	37.8
	330	37.0	330	255	-15.0	25.9	-52.3	29.7	11.9	38.5
	331	36.3	330	250	-13.5	24.7	-53.8	29.9	12.3	38.7
	332	35.2	330	235	-15.4	26.9	-53.2	30.7	13.4	39.0
	333	35.9	-324	260	18.5	-25.7	44.7	-27.2	-8.5	-37.7
	334	37.0	-326	229	14.7	-22.7	44.6	-26.2	-6.5	-35.5
	335	38.3	-327	209	16.6	-25.5	51.5	-26.1	-8.0	-34.7
	336	39.9	-328	200	14.4	-26.0	50.8	-25.2	-7.6	-35.3
	337	39.4	-329	255	15.3	-28.3	49.1	-26.3	-9.2	-36.1
	338	39.3	-329	253	16.3	-27.0	50.0	-28.9	-12.9	-35.8
	339	40.8	-329	257	16.0	-27.9	52.0	-27.3	-10.4	-35.3
	340	41.9	-328	227	17.1	-27.4	51.5	-26.6	-8.9	-35.7
	341	43.7	-327	256	15.5	-26.6	50.8	-25.5	-9.5	-35.4
	342	42.6	-328	256	14.2	-25.5	50.2	-26.0	-9.9	-35.7

7.2.2 J-Turn with Pulse Braking and Rollover Propensity

For both of the vehicles tested in Phase I-A, the Ford Bronco II and the Jeep Cherokee, two-wheel lifts were observed during the J-Turn With Pulse Braking testing. Both vehicles had both minor and moderate two-wheel lifts. Since neither of these vehicles had two-wheel lifts during the J-Turn (without Pulse Braking) in Phase I-A, this demonstrated that the addition of pulse braking to the J-Turn maneuver can result in higher, Post-Pulse, Maximum Corrected Lateral Accelerations and Roll Angles.

Also in Phase I-A, the limit conditions for the Ford Bronco II and the Jeep Cherokee in the J-Turn With Pulse Braking maneuver appeared to depend upon the direction in which the individual test run was made. For the Ford Bronco II, left turns (negative handwheel steer angle) produced two-wheel lift, but plow outs appeared to be the limit condition for this vehicle for right turns. It should be noted limited testing was performed in Phase I-A using the Bronco II in this direction. For the Jeep Cherokee, right turns produced two-wheel lift. Plow outs appeared to be the limit condition for this vehicle in left turns.

In Phase I-B, both of the drivers were able to produce two-wheel lift in both steer directions for the Bronco II, so there does not appear to be major symmetry differences for this vehicle. (The asymmetry suspected in Phase I-A was primarily caused by conducting very limited testing.) The Jeep Cherokee was not tested in Phase I-B.

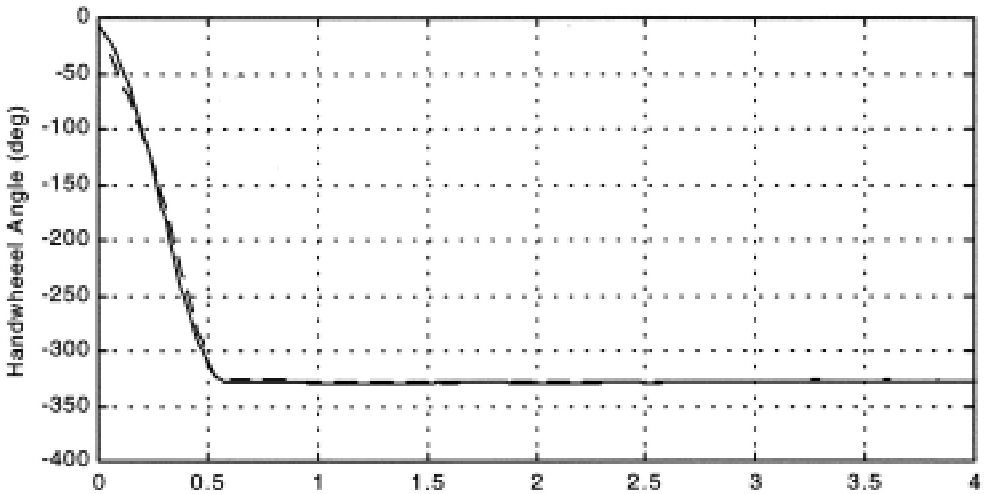
In Phase I-A it was found that both the Delta Lateral Acceleration and Delta Roll Angle (Delta = Post-Pulse - Pre-Pulse) increased with increasing brake magnitude. It was recommended that a 200 pound-force brake pulse be applied in later rollover research. Driver A had brake pedal forces that were slightly lower than 200 pounds-force on average while Driver C had brake pedal forces that were slightly higher. Both drivers were able to achieve two-wheel lift. The results found in this portion of the Phase I-B study suggest that the 200 pound-force brake application still appears to be a good level for later research. An examination of the effect of Brake Pulse Magnitude on test results is presented in Chapter 10 - Steering Controller Test Results and Analysis. The testing conducted for that part of the Phase I-B study is better suited for this type of analysis and therefore was not conducted on the data presented in this chapter.

The J-Turn With Pulse Braking maneuver is expected to induce two-wheel lift for many vehicles. The initial test speed appears to be a measure that can be used to quantify a vehicle's rollover propensity.

7.2.3 Driver Variability Effects on the Repeatability of the J-Turn with Pulse Braking Maneuver

Example handwheel angle and braking inputs supplied by Driver's A and C are given in Figure 7.18. These two tests (289 and 336) had similar initial speeds (39.8 $\pm$ 0.1mph) Driver A has a faster steering rate than Driver C for these two tests. From Table 7.4, Driver A generally had a larger Peak Handwheel Rate than Driver C. Also from Table 7.4, Driver C generally had a larger Pulse Brake Magnitude and Duration. The typically larger and earlier pulse brake input given by Driver C can be seen in Figure 7.18.

The longitudinal and lateral acceleration traces for Tests 289 and 336 are given in Figure 7.19. From Table 7.4, The higher and earlier pulse brake input given by Driver C generally resulted in larger Deceleration due to Turn and Brake values. Driver C had a generally lower Deceleration due to Turn. This occurred because Driver C tended to apply the brake pulse sooner, relative to the initial steering input, than Driver A. These typical results are evident in the longitudinal acceleration traces presented in Figure 7.19. The delayed braking (relative to Driver C) for Driver A allows the longitudinal acceleration to reach a higher level prior to the pulse brake application (Deceleration due to Turn).



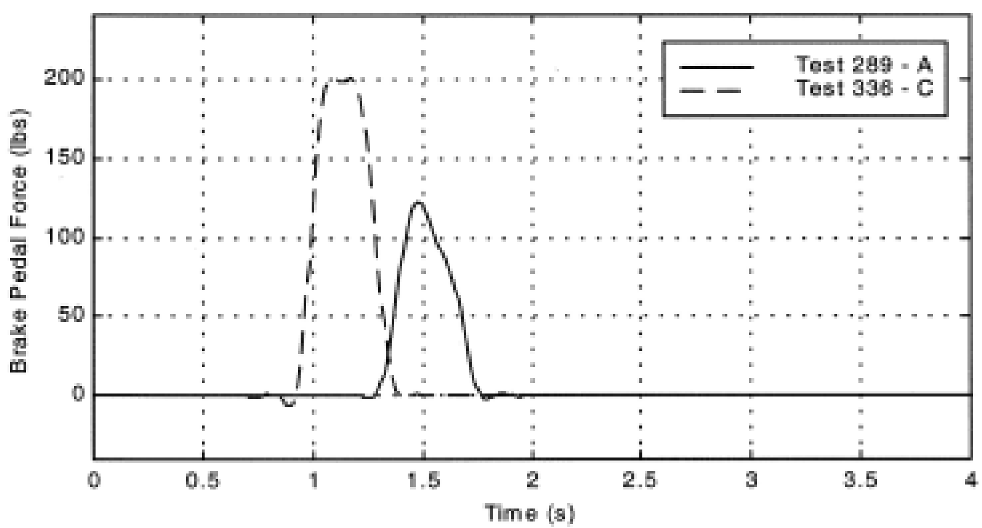


Figure 7.18 -- J-Turn with Pulse Brake Driver Comparison - Handwheel Angle and Brake Pedal Force

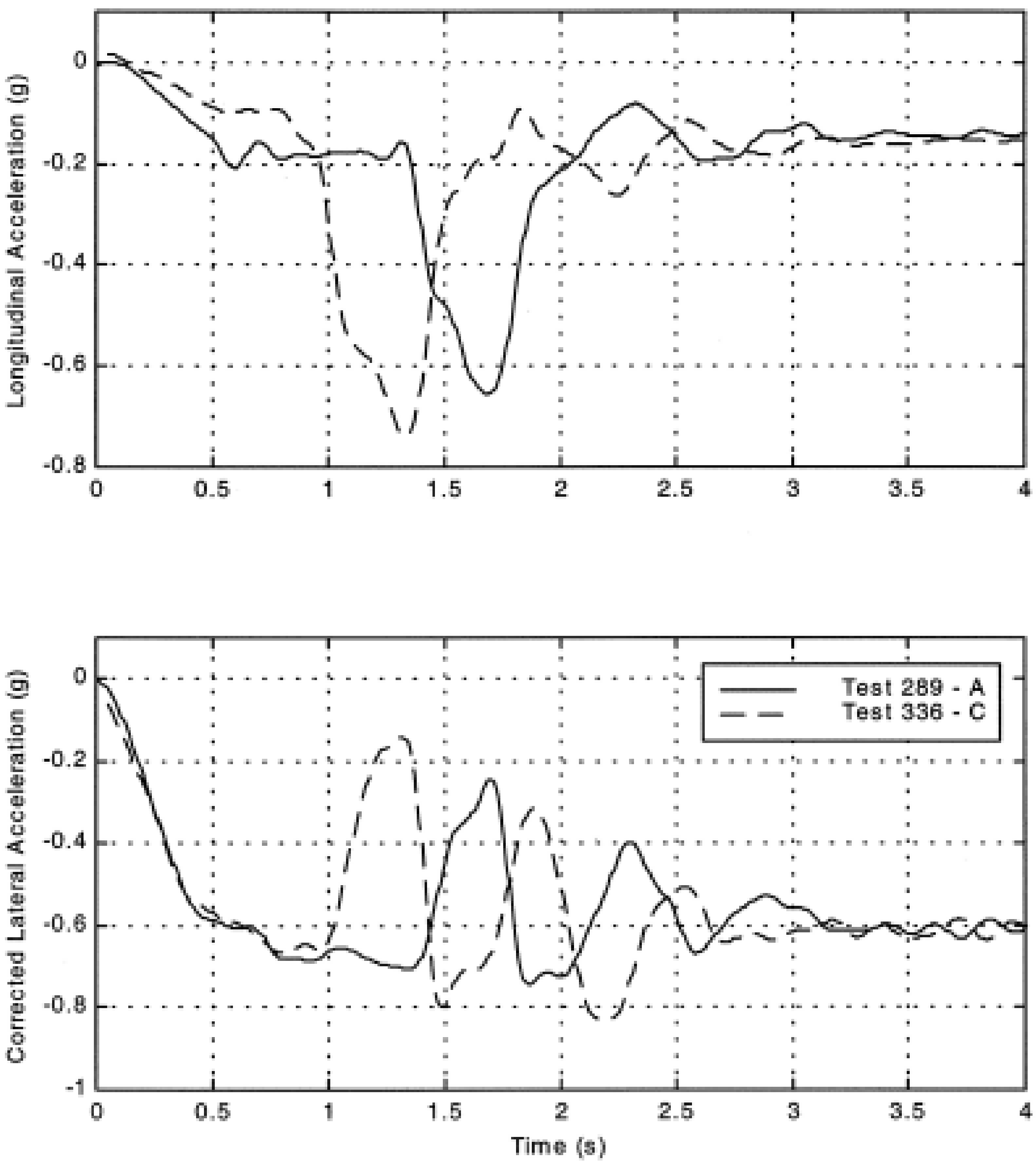


Figure 7.19 -- J-Turn with Pulse Brake Driver Comparison - Longitudinal Acceleration and Corrected Lateral Acceleration

The higher pulse brake application for Driver C results in a higher magnitude Deceleration due to Turn and Brake value. The faster on-set of braking for Driver C can result in lower Pre-Pulse Peak Corrected Lateral Acceleration values as seen in Figure 7.19. The larger Pulse Brake Magnitude for Driver C resulted in a greater Dip due to Pulse Corrected Lateral Acceleration and a higher Post-Pulse Peak Corrected Lateral Acceleration. The results presented in Figure 7.19 are fairly representative of the results for Drivers A and C.

The roll angle and roll rate traces for Tests 289 and 336 are given in Figure 7.20. The larger Pulse Brake Magnitude produced by Driver C resulted in a greater Dip for the Roll Angle values compared to Driver A (Table 7.5). The larger Pulse Brake Magnitudes (for Drivers A and C) would produce Roll Angle Dip due to Pulse values that were in the opposite direction of the initial roll angle. The results presented in Figure 7.20 show how a larger Pulse Brake Magnitude increases the Roll Angle Dip. The Pre-Pulse Peak Roll Rate for Driver A is higher than that for Driver C. These values occur well before the pulse brake input. Driver A's value is probably higher due to the higher steering rate. In general, the Pre-Pulse Peak Roll Rate values are fairly similar for the two drivers (Table 7.6). The Roll Rate Dip due to Pulse and the Peak Roll Rate, Post Pulse are much higher for Driver C due to the higher Pulse Brake Magnitude supplied by this driver.

From the results presented in Table 7.6, the Yaw Rate Pre-Pulse values are very similar for the two drivers. Some of the Yaw Rates for Driver C are lower due to the earlier timing of the brake pulse, i.e., the vehicle had not reached a yaw rate peak prior to the pulse being applied. The Yaw Rate Dips due to Pulse are also greater for the larger Pulse Brake Magnitudes, but the Peak Yaw Rates Post-Pulse are not. The Peak Yaw Rates Post-Pulse generally occur well after the pulse brake application and therefore are not heavily influenced by it.

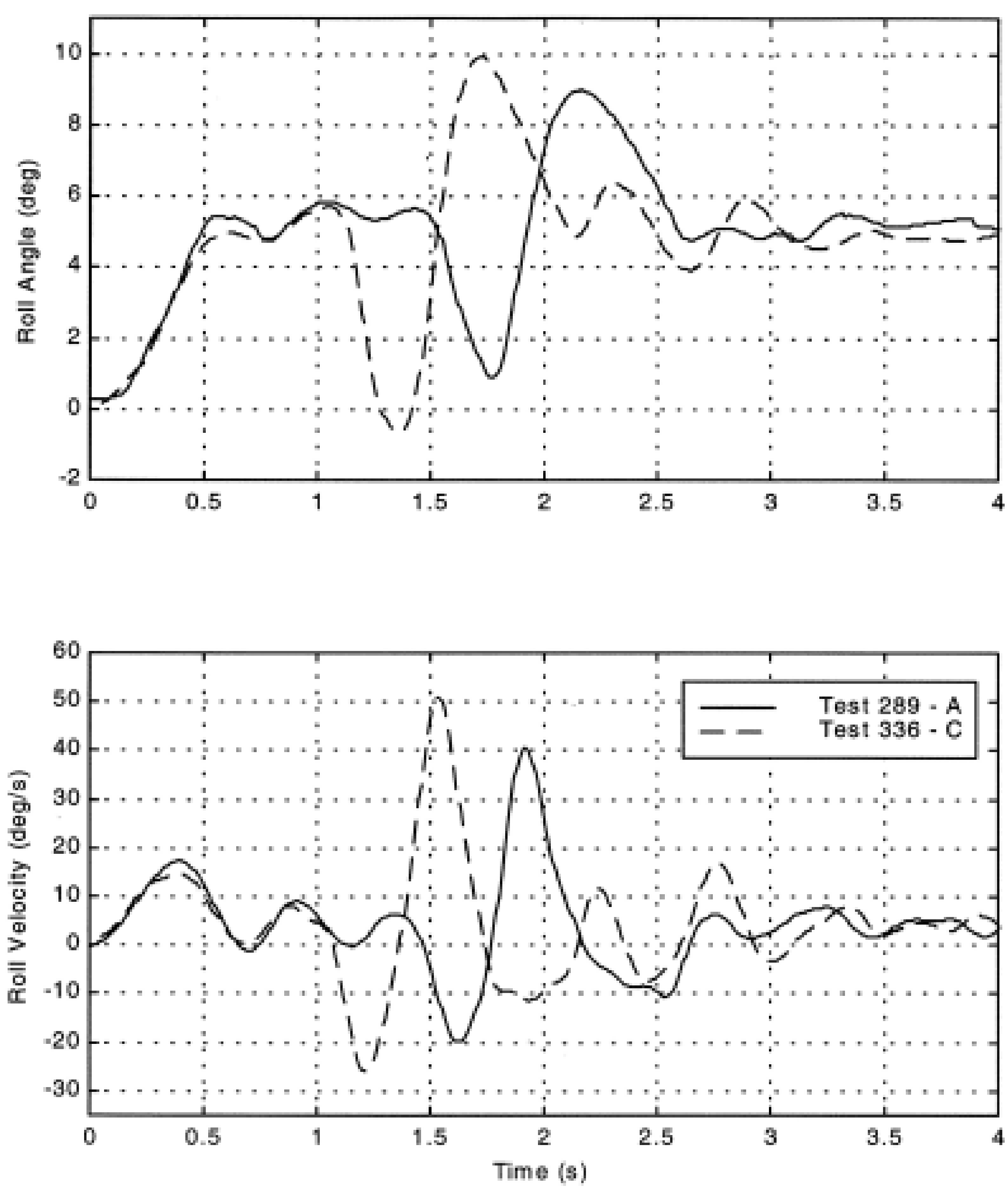


Figure 7.20 -- J-Turn with Pulse Brake Driver Comparison - Roll Angle and Roll Velocity

The Pulse Brake Magnitude differences for Drivers A and C did not necessarily result in two-wheel lift at lower speeds or lateral accelerations for either driver. As seen in Table 7.7, Driver A and Driver C had Minimum Initial Speeds Required to Produce Two-Wheel Lift that were in the same range (36 to 42 mph for all combinations of steering direction and replication).

Table 7.7 -- Minimum Initial Vehicle Speed Required to Produce Two-Wheel Lift for J-Turn with Pulse Braking Tests

Driver	Right	Left
A	36.3 40.1	42.0 38.4
C	35.9	39.3

The Minimum Corrected Lateral Accelerations that resulted in two-wheel lift for each combination of steering direction, driver, and test set are given in Table 7.8. The variability for the Right Steer direction is relatively large (0.83 to 0.92 g). The left steer results are somewhat less variable (-0.82 to -0.87 g). The values for Driver C were within the range of those found for Driver A. This further suggests that driver differences did not have a large influence on results.

Table 7.8 -- Minimum Corrected Lateral Acceleration Values for J-Turn with Pulse Braking Two-Wheel Lift

Driver	Right	Left
A	0.92 0.83	-0.82 -0.87
C	0.87	-0.87

The LAR values for each combination of steering direction, driver, and test set are given in Table 7.9. These values are much less variable than the Minimum Corrected Lateral Acceleration values listed in Table 7.8 (0.86 to 0.87 g for Right steer and -0.82 to -0.85 g for Left steer). This suggests that having multiple instances of no two-wheel lift and two-wheel lift helps to "filter" the test results and produce a fairly consistent answer. This result also suggests that driver differences did not have a large influence on test results. It should be noted that one of the test sets did not have any instances of no two-wheel lift. For this case, the minimum lateral acceleration that did produce two-wheel lift was used.

Table 7.9 -- LAR Values for J-Turn with Pulse Braking Tests

Driver	Right	Left
A	0.86 0.86	-0.82 -0.82
C	0.87*	-0.85

*- all tests for this condition had two-wheel lift, the lowest lateral acceleration value is listed

7.2.4 J-Turn with Pulse Braking Problems

At times it was difficult to tell whether or not two-wheel lift had occurred. Only after close examination of the video could two-wheel lift determination be made. This resulted in one test set having two-wheel lift for every test conducted. If all two-wheel lifts had been noted during the course of testing, the vehicle speed would have been lowered until a no two-wheel lift test was achieved.

7.2.5 Summary of Driver Controlled J-Turn with Pulse Braking Results

Two drivers conducted a limited number of J-Turn with Pulse Braking tests with the 1984 Ford Bronco II. Driver A completed two sets of tests for each steering direction while Driver C completed one set.

For both of the vehicles tested in Phase I-A, the Ford Bronco II and the Jeep Cherokee, two-wheel lifts were observed during the J-Turn With Pulse Braking testing. The limit conditions for the Ford Bronco II and the Jeep Cherokee in the J-Turn With Pulse Braking maneuver appeared to depend upon the direction in which the individual test run was made. In Phase I-B, both of the drivers were able to produce two-wheel lift in both steer directions for the Bronco II, so there does not appear to be major symmetry differences for this vehicle. (The asymmetry suspected in Phase I-A was primarily caused by conducting very limited testing.) The Jeep Cherokee was not tested in Phase I-B and therefore no further comment on the asymmetries observed for that vehicle can be made.

For Phase I-B testing, Driver A generally had a larger Peak Handwheel Rate than Driver C. Driver C generally had a larger Pulse Brake Magnitude and Duration. While these differences produced test-to-test variations, the overall test results for each driver were fairly similar. Driver A and Driver C had Minimum Initial Speeds Required to Produce Two-Wheel Lift that were in the same range (36 to 42 mph for all combinations of steering direction and replication). The LAR values for each combination of steering direction, driver, and test set are very similar as well (0.86 to 0.87 g for Right steer and -0.82 to -0.85 g for Left steer).

LAR values were much less variable than the Minimum Lateral Accelerations Required to Produce Two-Wheel Lift. This suggests that having multiple instances of no two-wheel lift and two-wheel lift tests and then taking the average of the minimum lateral acceleration for the two-wheel lift cases and the maximum lateral acceleration for the no two-wheel lift cases (calculation of an LAR) helps to “filter” the test results and produce a fairly consistent answer.

The J-Turn With Pulse Braking maneuver is expected to induce two-wheel lift for many vehicles. The initial test speed appears to be a measure that can be used to quantify a vehicle’s rollover propensity.

7.3 Fishhook Without Pulse Braking Maneuver Test Results and Analysis - Driver Effects

Fishhook Without Pulse Braking tests were performed by three drivers. The results from these tests are presented below. Driver effects are examined and a general assessment of the Fishhook Without Pulse Braking maneuver is given.

7.3.1 Fishhook Without Pulse Braking Tests Performed for Each Vehicle

Fishhook testing was performed by three drivers using both the 1990 Toyota 4Runner and 1984 Bronco II. Testing was also performed with a steering controller and those test results are presented in Chapter 10. The driver tests focused on driver repeatability, the influence of outriggers on results, and the influence of fuel level on results. Outrigger influences were examined using several analysis techniques and test maneuvers. All of the outrigger test results will be presented in Chapter 8. The effect of fuel level will be presented in Chapter 9. The effect of tire size for the Toyota 4Runner was also examined and will be presented below.

The initial (baseline) testing examined driver repeatability. All of these tests were conducted with a low fuel level (less than 1/4 of a tank). For each test set, tests were conducted with both a Right-Left steering input and a Left-Right steering input. It was intended that testing be conducted until three tests with two-wheel lift were achieved so a Lateral Acceleration at Rollover (LAR) value could be determined. The initial steering magnitude was 270 degrees and was controlled using a steering stop. The results from this testing are presented in Sub-Section 7.3.2.

Fishhook tests were also performed with the 4Runner using the smaller tire size (P225/75R15) that is available for the vehicle. The initial tests were done with a smaller rim size, but after a tire debeading, the smaller tires were mounted on the rims normally used for the larger tire size (31x10.50R15LT). All other tests were done with the larger tire size. All of the smaller tire tests were performed by the same driver (Driver C). These results are presented in Sub-Section 7.3.3. Peak vehicle responses for all of the driver controlled Fishhook tests are given in Appendix A.

7.3.2 Baseline Fishhook Test Results - Driver Comparison

Fishhook testing was performed by three drivers using both the 1990 Toyota 4Runner and 1984 Bronco II. The primary focus of this sub-section will be on Initial Speed and Lateral Acceleration at Rollover (LAR) values for various vehicle/driver combinations, but an examination of several "matched" tests will be presented first.

Peak driver input/vehicle response values from three sets of "matched" tests are given in Table 7.10. The tests are matched based on the initial test speed. The nominal initial steer angle for all of the tests was controlled with a steering stop and was set at 270 degrees. The Vehicle, Driver, Test Number, and Initial Speed are listed in Table 7.10. The First and Second Peak (first steer and second steer peak) values for Handwheel Angle, Lateral Acceleration, Roll Angle, Roll Rate, and Yaw Rate are also given. Only the Peak Yaw Rate for First Steer is given because the Second Steer Peaks occur very late in the maneuver (well past Peak Roll Angle and Lateral Acceleration) and are not relevant.

Table 7.10 -- First and Second Peak Vehicle Response Data for Matched Fishhook Tests

Vehicle	Driver	Test No.	Initial Speed (mph)	Peak Handwheel Angle (deg)		Peak Lateral Acceleration (g)		Peak Roll Angle (deg)		Peak Roll Rate (deg/sec)		Peak Yaw Rate (deg/sec)
				First	Second	First	Second	First	Second	First	Second	First
4Runner	A	41	35.2	-275	709	-0.66	0.77	6.6	-9.1	20.0	-42.9	-33.5
	B	78	35.4	-271	466	-0.64	0.77	7.1	-9.3	18.4	-28.6	-29.4
	C	111	35.1	-275	738	-0.67	0.69	6.9	-7.8	20.8	-28.8	-29.2
4Runner	A	32	35.0	269	-767	0.70	-0.78	-6.8	9.3	-17.3	36.3	32.4
	A	38	35.1	268	-768	0.71	-0.72	-6.9	9.7	-18.2	40.9	31.7
	A	58	35.2	270	-778	0.71	-0.80	-7.2	9.4	-22.5	43.2	33.7
	B	68	35.0	260	-511	0.65	-0.73	-6.8	9.0	-18.6	30.8	29.2
	C	99	35.0	273	-780	0.63	-0.74	-6.4	10.3	-14.4	33.0	29.6
	C	106	35.0	268	-793	0.66	-0.76	-6.5	10.0	-21.4	31.9	30.7
Bronco II	A	33	42.7	278	-540	0.76	-0.78	-5.6	7.6	-17.3	34.1	29.8
	B	180	43.0	276	-463	0.66	-0.72	-5.3	9.0	-11.6	27.5	24.2
	C	357	43.0	267	-764	0.71	-0.72	-5.6	8.2	-18.6	34.9	28.0

Tests 41-Driver A, 78-Driver B, and 111-Driver C are matched tests with Left-Right steering inputs and an Initial Vehicle Speed of approximately 35.2 mph. The vehicle speed, handwheel angle, corrected lateral acceleration, and roll angle traces for these tests are given in Figures 7.21 and 7.22. The vehicle speed trace for Test 111 has a spike in it near 2.75 seconds. This spike is not real and is due to the fifth wheel losing contact with the ground. Other than this spike, the vehicle speed traces for Tests 78 and 111 are fairly similar, but Test 41 is slightly lower as the tests proceed through the steering reversal. The First Peak Handwheel Angles are very similar for the three drivers due to the steering stop employed during testing. The Second Peak Handwheel Angles are quite different and the timing of the steering reversal is fairly different as well. Driver C in particular held the handwheel against the steering stop for a longer duration than the other drivers for this first set of matched tests.

The First Peak Lateral Accelerations and Peak Roll Angles are very similar for this first set of matched tests ranging from -0.64 to -0.67 g and 6.6 to 7.1 degrees respectively. Examining the results in Figure 7.22 show that even though Driver C holds the initial steering input slightly longer, the lateral acceleration and roll angles do not necessarily reach a greater value. This suggests that the tires are saturated and the vehicle has reached a peak response for all three drivers.

The Second Peak Lateral Accelerations and Peak Roll Angles are more varied than the First Peak values for the first set of matched tests ranging from 0.69 to 0.77 g and -7.8 to -9.3 degrees respectively. Driver C's Second Peak values were considerably lower than those for Drivers A and B even though Driver C had the largest Second Peak Handwheel Angle. The lower values for Driver C may be due to the delay in the timing of the steering reversal (compared to Drivers A and B). The roll angle traces presented in Figure 7.22 show that the Peak Roll Angle can sometimes occur on the first roll peak after the steering reversal or on later roll peaks. This issue was fully discussed in the Phase I-A report [1].

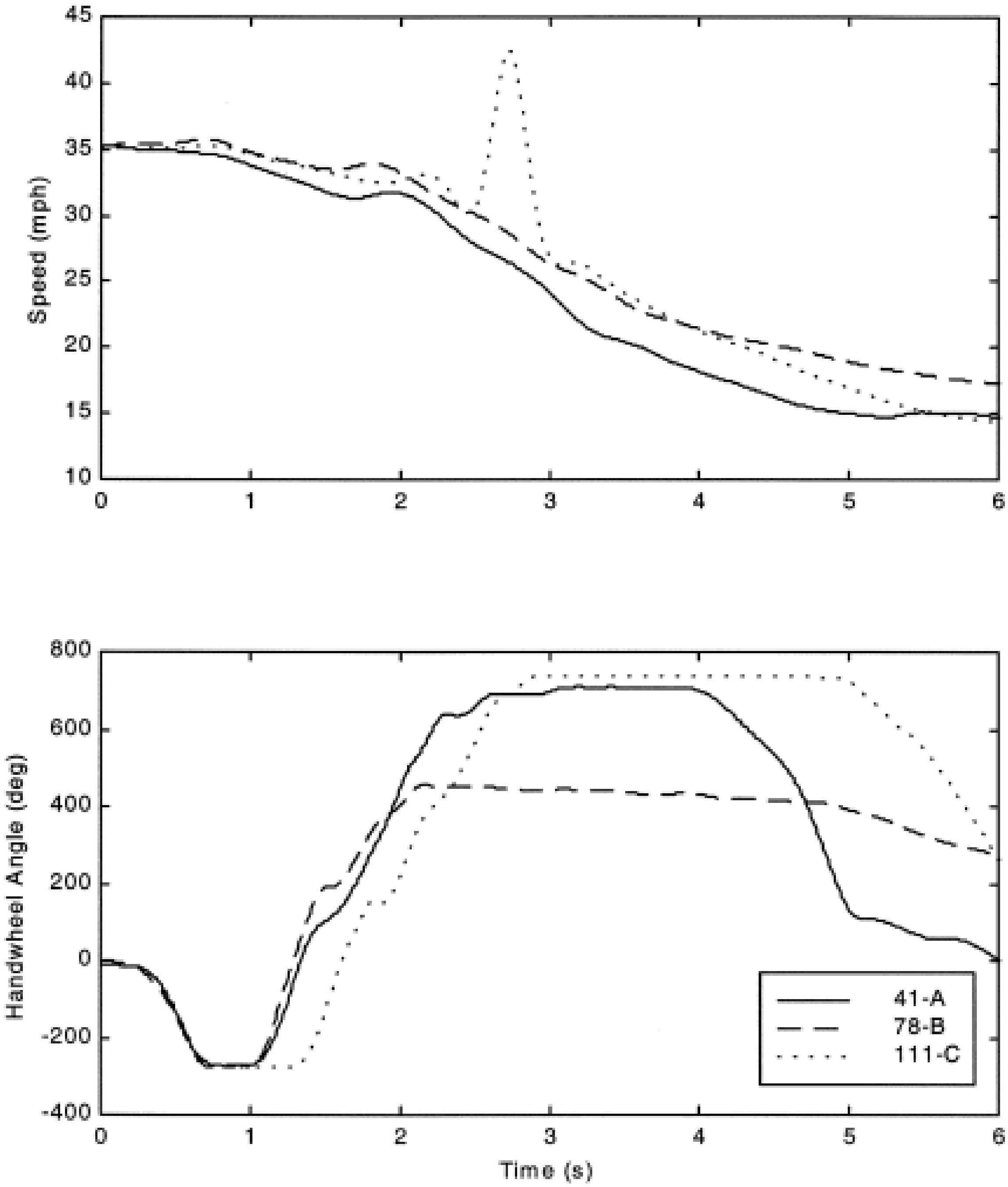


Figure 7.21 -- Vehicle Speed and Handwheel Angle for 4Runner Matched Tests 41-A, 78-B, and 111-C

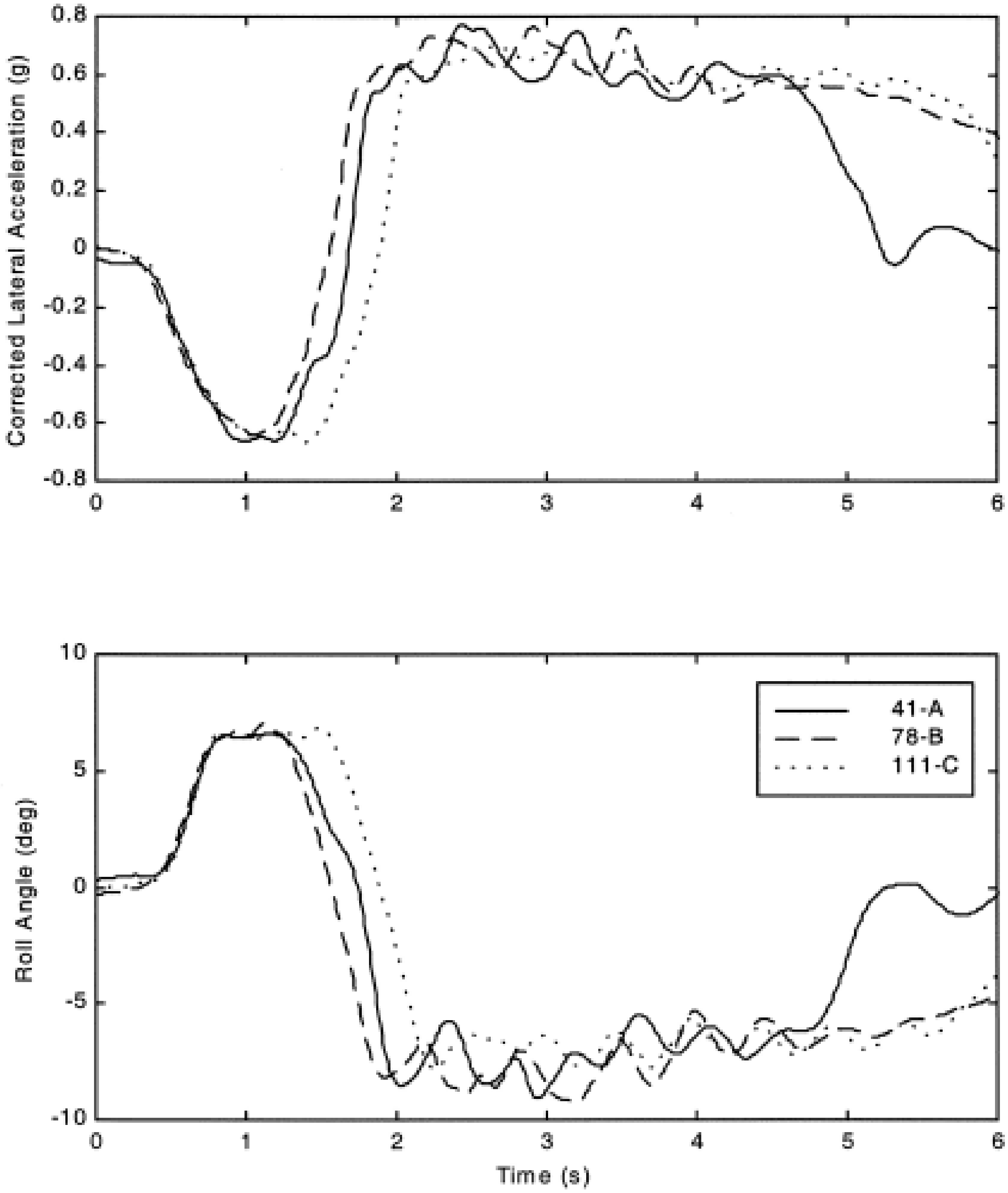


Figure 7.22 -- Lateral Acceleration and Roll Angle for 4Runner Matched Tests 41-A, 78-B, and 111-C

The vehicle speed, handwheel angle, corrected lateral acceleration, and roll angle traces for the second set of matched tests presented in Table 7.10 are given in Figures 7.23 and 7.24. Even though the initial speeds for these tests are very similar (35.0 mph nominal), the speeds for Driver A tend to drop off slightly more than those for the other drivers. This may be due to the fact that Driver A tended to hold the handwheel against the steering stop longer than the other driver for these tests.

Driver C had the fastest steering reversals which is the opposite of what was seen for the first set of matched tests. This set of tests is in the opposite steer direction of that for the first set of matched tests, so the driving "style" may be different for each driver depending on initial steering direction. Drivers A and C reach the maximum steering input on the steering reversal, while Driver B had a Second Peak Handwheel Angle of 511 degrees. Even though this is somewhat less than the other drivers, it is still high enough to saturate the tires.

Drivers B and C had lower First Peak values than Driver A, probably due to their faster steering reversal timing. They had Second Peak values that fell within the range for Driver A.

The First Peak Roll Angle values for Driver C are slightly lower than the one for Driver B. The one value for Driver B is on the low end of that for Driver A. As seen in Figure 7.24, these results are probably due to the faster timing of the steering reversal for Drivers C and B. Driver C had the highest Second Peak Roll Angle values. These higher values may be due to the speed of steering reversal; however, Driver B had lower Second Peak values than both Driver A and C even though his steering reversal timing fell between those for Drivers A and C.

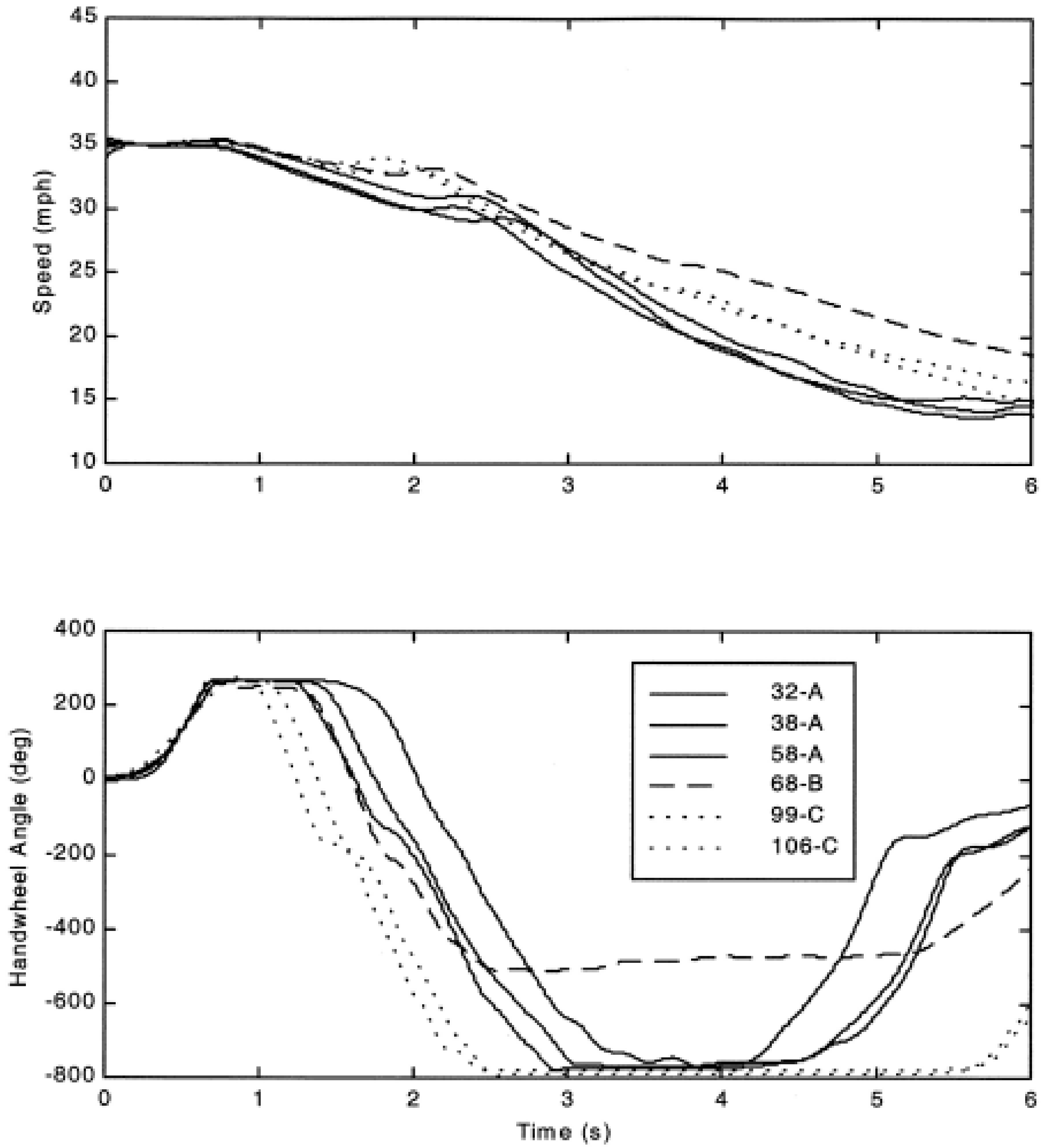


Figure 7.23 -- Vehicle Speed and Handwheel Angle for 4Runner Matched Tests 32-A, 38-A, 58-A, 68-B, 99-C and 106-C

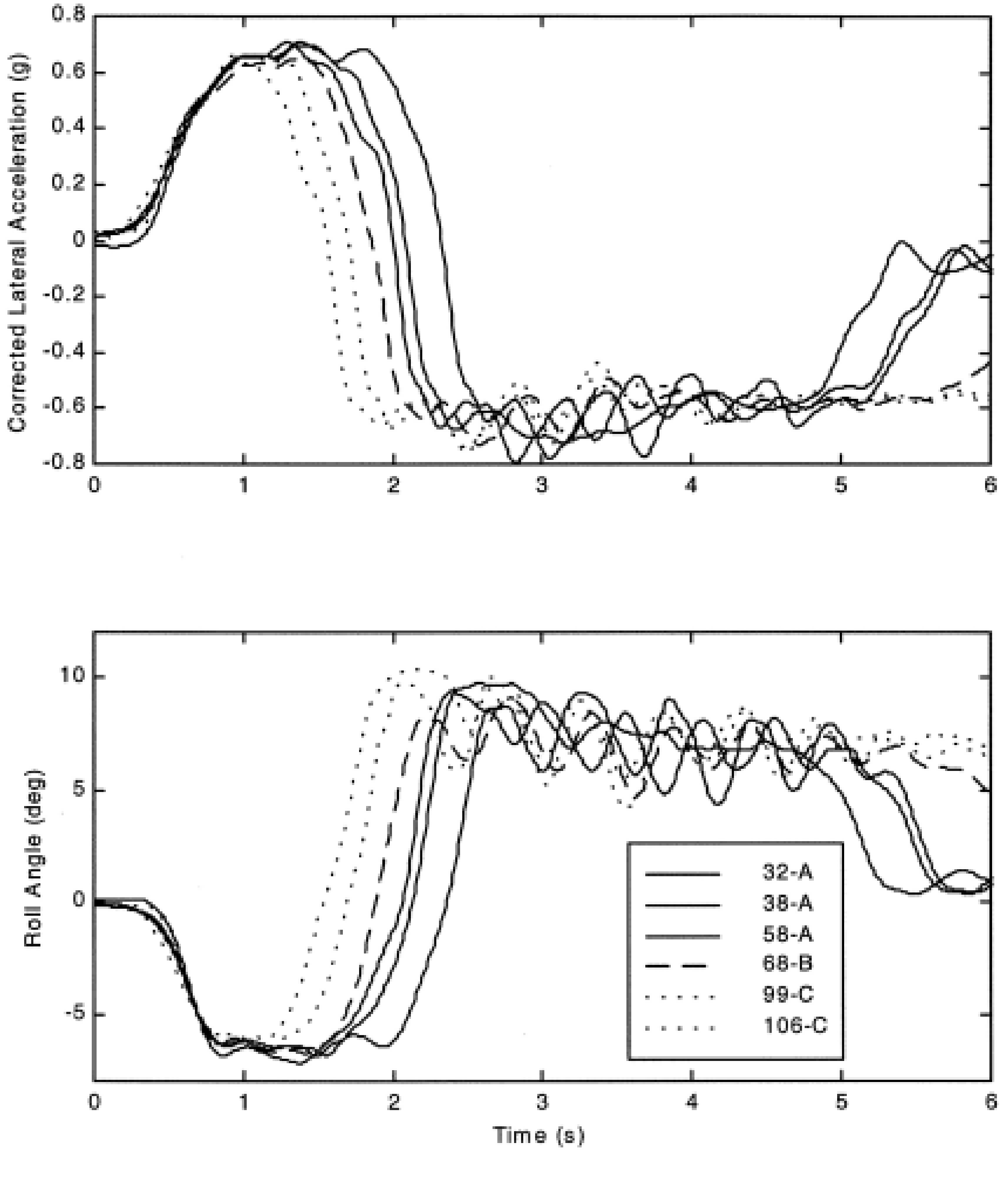


Figure 7.24 -- Lateral Acceleration and Roll Angle for 4Runner Matched Tests 32-A, 38-A, 58-A, 68-B, 99-C and 106-C

The third set of matched pair tests presented in Table 7.10 were Right-Left, 42.8 mph (nominal) tests conducted with the Ford Bronco II. The vehicle speed, handwheel angle, corrected lateral acceleration and roll angle traces for these tests are given in Figures 7.25 and 7.26. The initial handwheel input for Driver B (Test 180) was much slower than those for the other two drivers. The steering reversal timing for Driver A was much slower than that for Drivers B and C.

The slower initial steer for Driver B appears to have been the cause for lower First Peak Lateral Acceleration and Roll Angle values. Driver A had the largest Second Peak Lateral Acceleration, but the smallest Second Peak Roll Angle value. The slower steering reversal timing appears to have contributed to this lower Second Peak Roll Angle value.

Test 357 had a drop in Lateral Acceleration and Roll Angle between 3 and 4 seconds that was not present in the other two tests. The reasons for this drop are not known. However, it is thought to have had no effect on the test results of primary interest for rollover research.

In general, it appears driver differences can have an affect on individual test results. The following analysis will examine overall test results. In particular, Lateral Acceleration at Rollover (LAR) and Minimum Initial Speed Required to Produce Two-Wheel Lift values will be presented.

The baseline LAR values are given in Tables 7.11 and 7.12. All of the baseline tests were conducted with a low fuel level (less than 1/4 of a tank). As described in the Phase I-A test report, the Toyota 4Runner sometimes would lift on the first roll peak after the steering reversal and on other occasions would lift on the second roll peak. The Bronco II did not have this tendency. The first roll peak data for both vehicles are given in Table 7.11, while the second peak data for the 4Runner are given in Table 7.12. Average, standard deviation, and coefficient of variation values are given in each table.

For the Toyota 4Runner First Peak values given in Table 7.11, the Left-Right steer (initial steer to the left followed by a steering reversal to the right) tests produced LAR values ranging from 0.62 to 0.66 g with an average of 0.64 g, while the Right-Left steer produced values ranging from -0.64 to -0.67 g with an average of -0.66 g. All of the 4Runner LAR values are within 0.02 g of the average values. The 4Runner Left-Right average LAR value is only 0.02 g less than that for the Right-Left steer direction and there is some overlap in the data for these two steer combinations. The standard deviation values were relatively low for the 4Runner (0.016 and 0.011 g) which resulted in low coefficient of variation values (2.6 and -1.7%). The small coefficient of variation values suggest that the drivers did not have major differences in LAR values. The drivers did not perform the same number of test series for each test condition and the number of test series are limited (1,2, or 3 test series/driver), so a proper statistical analysis can not be made, but the limited data collected suggests that there were no major driver differences in determining LAR for the Toyota 4Runner. (Toyota 4Runner Tests 40-42 (Driver A) are listed as N.A. because not enough tests were performed to calculate an appropriate LAR value.)

Table 7.11 -- LAR Values Using First Peak - Driver Comparison for the Bronco II and the Toyota 4Runner with Larger Tires and Low Fuel

Driver	Toyota 4Runner				Bronco II			
	Left-Right		Right-Left		Left-Right		Right-Left	
	Tests	LAR (g)	Tests	LAR (g)	Tests	LAR (g)	Tests	LAR (g)
A	040-042	N.A.	030-038	-0.67	003-013	0.78	014-026	-0.70
	045-053	0.64	055-061	-0.66	043-050	0.76	029-042	-0.71
					258-268	0.75	269-276	-0.72
B	075-081	0.64	067-074	-0.66	187-195	0.75	169-186	-0.71
C	084-094	0.66	095-102	-0.64	347-355	0.82*	356-364	-0.76
	110-115	0.62	105-109	-0.66				
Average		0.64		-0.66		0.76		-0.72
Std. Dev.		0.016		0.011		0.014		0.023
Coef. of Var.		2.6%		-1.7%		1.9%		-3.3%

* - No tests had two-wheel lift - max value listed - not used in calculated statistical results

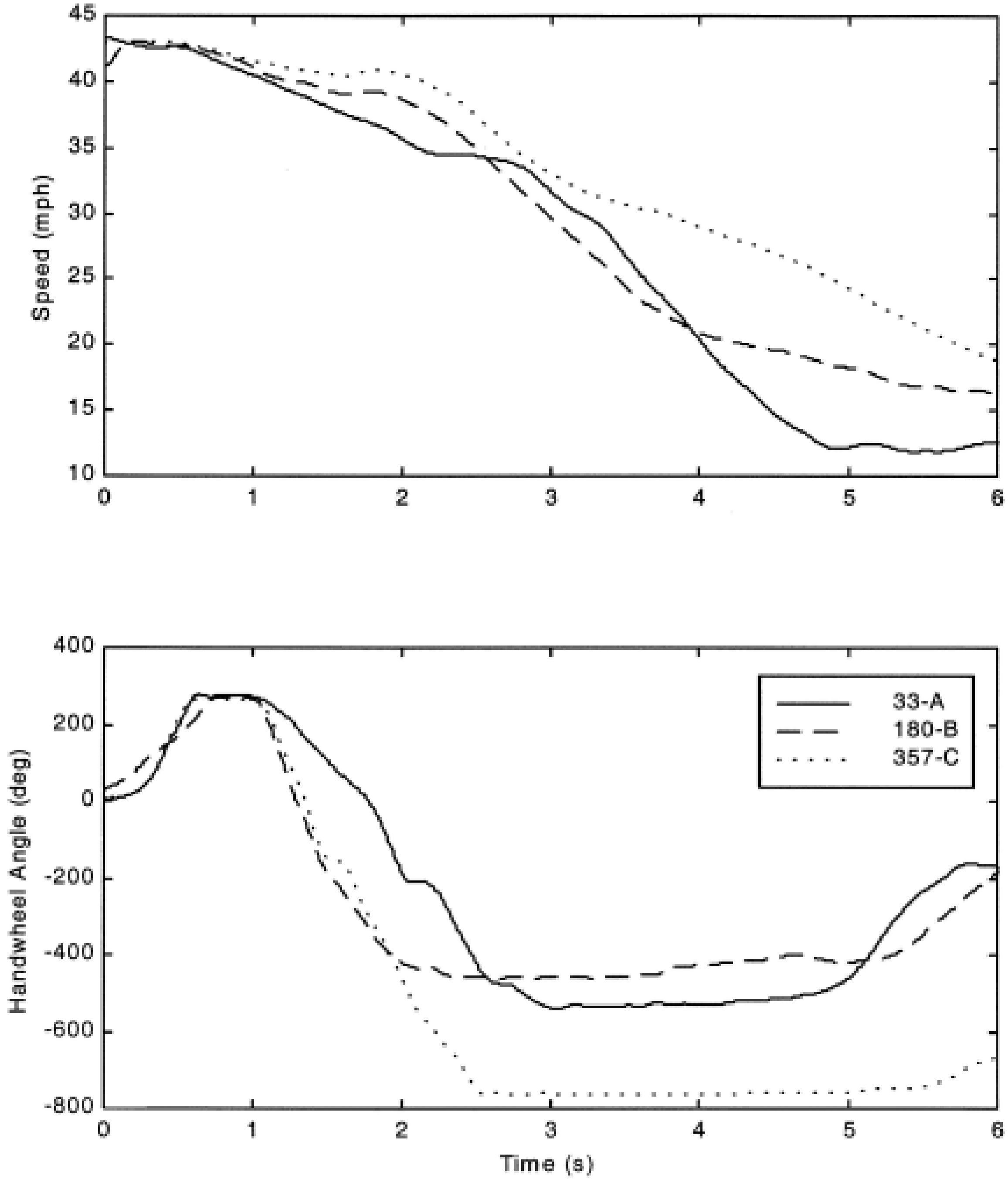


Figure 7.25 -- Vehicle Speed and Handwheel Angle for Bronco II Matched Tests 33-A, 180-B, and 357-C

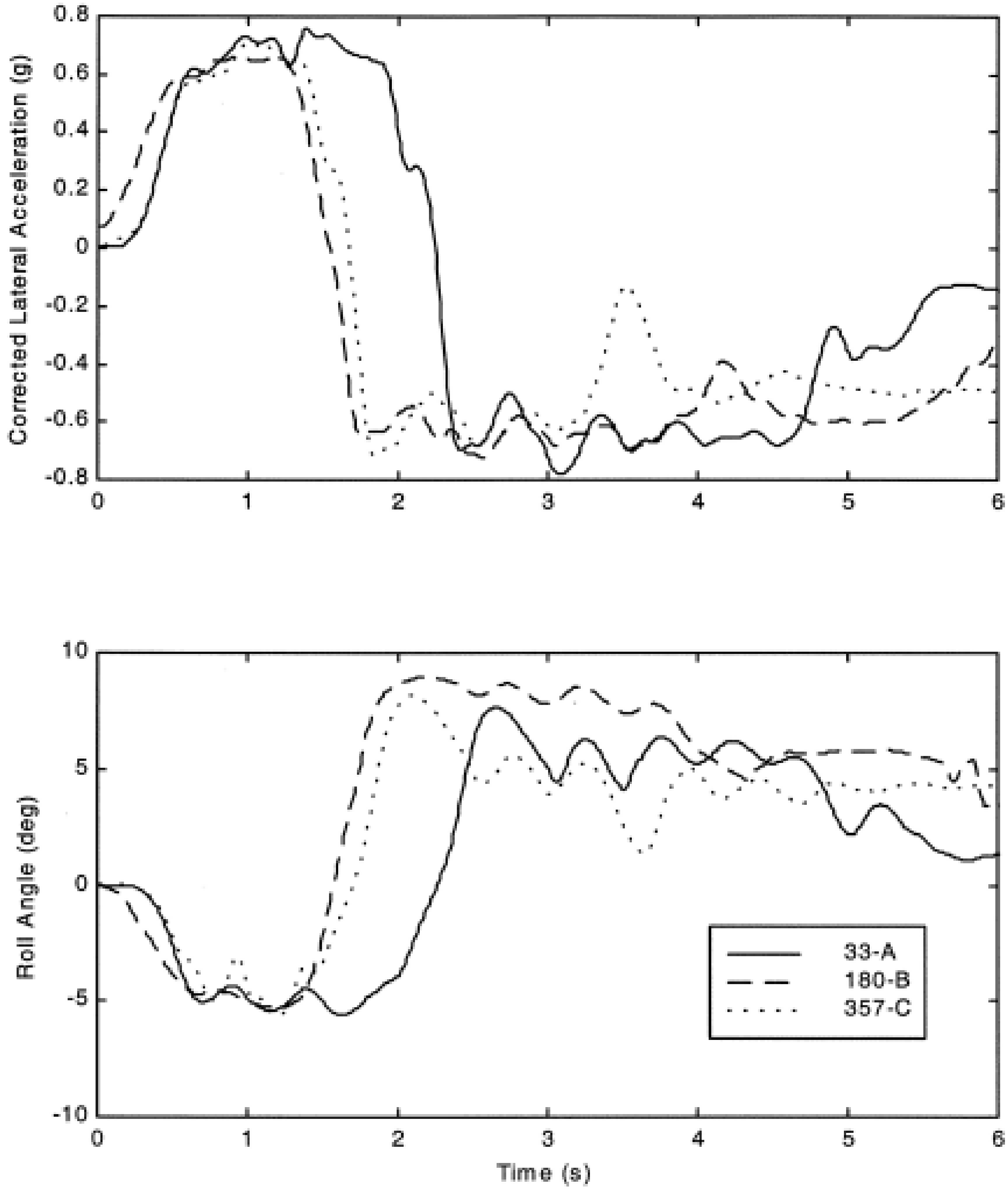


Figure 7.26 -- Lateral Acceleration and Roll Angle for Bronco II Matched Tests 33-A, 180-B, and 357-C

The Bronco II had Left-Right steer LAR values ranging from 0.75 to 0.78 g with an average of 0.76 g, while the Right-Left steer produced values ranging from -0.70 to -0.76 g with an average of -0.72 g. The Bronco II average LAR value for the Left-Right steer combination is 0.04 g greater than that for the Right-Left steer combination, but there is some overlap in the range of values for each of these steer combinations. The standard deviation values for the Bronco II (0.014 and 0.023 g) were similar to those found for the 4Runner. The coefficient of variation values for the Bronco II were 1.9 and -3.3%. Drivers B and C only completed one set of tests for each steer combination. The LAR values for Driver B fell within the range of values for Driver A who completed three sets of tests for each steer combination. Driver C's Left-Right tests (347-355) did not produce two-wheel lift. This is probably primarily due to a tire wear issue more than a driver difference issue. As detailed in the Phase I-A report [1], the Bronco II tended to produce two-wheel lift in this maneuver only after significant tire wear had occurred. This will be explained further after the Minimum Initial Vehicle Speed Required to Produce Two-Wheel Lift results are presented (Table 7.12). Driver C's Right-Left tests produced a higher LAR value than those for Drivers A and B.

It should be noted that in general when a test sequence is performed, the highest lateral acceleration that did not produce two-wheel lift is generally higher than the lowest lateral acceleration that did produce two-wheel lift, i.e., there is some overlap in the lateral acceleration values that produce and that do not produce two-wheel lift. Since this is the case, when no two-wheel lifts are noted and the largest lateral acceleration for the non-two-wheel lift case is given, it is probably artificially high (slightly). If all the tests result in two-wheel lift then the lowest lateral acceleration given is probably somewhat low.

The Minimum Initial Speed Required to Produce Two-Wheel Lift values are given in Table 7.12. For the Toyota 4Runner, the Left-Right steer tests had Minimum Initial Speed values ranging from 36.2 to 37.8 mph with an average of 37.1 mph, while the Right-Left steer produced values ranging from 32.5 to 35.5 mph with an average of 34.5 mph. The 4Runner Minimum Initial Speeds for the Left-Right steer direction are all higher than those for the Right-Left direction. The standard deviation values were relatively low for the 4Runner (0.75 and 1.18 mph) which resulted in low coefficient of variation values (2.0 and 3.4%). As stated previously, this is a very limited data set, but it appears that the drivers were able to produce two-wheel lift at very similar Minimum Initial Speeds with some overlap in values for each driver.

Table 7.12 -- Minimum Initial Speed Required to Produce Two-Wheel Lift - Driver Comparison for the Bronco II and the Toyota 4Runner with Larger Tires and Low Fuel

Driver	Toyota 4Runner				Bronco II			
	Left-Right		Right-Left		Left-Right		Right-Left	
	Tests	Speed (mph)	Tests	Speed (mph)	Tests	Speed (mph)	Tests	Speed (mph)
A	040-042	N.A.	030-038	35.1	003-013	39.1	014-026	43.6
	045-053	36.7	055-061	34.5	043-050	38.4	029-042	42.0
					258-268	46.6	269-276	40.2
B	075-081	37.6	067-074	35.5	187-195	39.3	169-186	44.2
C	084-094	37.8	095-102	32.5	347-355	>48.1*	356-364	46.2
	110-115	36.2	105-109	35.0				
Average		37.1		34.5		40.9		43.2
Std. Dev.		0.75		1.18		3.85		2.27
Coef. of Var.		2.0%		3.4%		9.4%		5.2%

* - No tests had two-wheel lift, max initial speed listed - not used in calculated statistical results

The Bronco II had Left-Right steer Minimum Initial Speed values ranging from 39.1 to over 48.1 mph with an average of 40.9 mph (average does not include the over 48.1 mph value), while the Right-Left steer produced values ranging from 40.3 to 46.3 mph with an average of 44.0 mph. These wider ranges resulted in higher standard deviation values (3.85 and 2.27 mph) for the Bronco II compared to those found for the 4Runner. This, in turn, resulted in higher coefficient of variation values as well (9.4 and 5.2%).

As stated previously, no two-wheel lift occurred during Bronco II, Left-Right Tests 347-355 (Driver C). The minimum initial speed required to produce two-wheel lift is listed as greater than 48.1 mph in Table 7.12. This is the maximum initial speed for Tests 347-355. Even though two-wheel lift was not achieved, the driver felt that the vehicle may come up hard against the outriggers if the testing were to continue up to higher speeds and therefore testing ceased for this steering combination and Right-Left steer combination testing was started for this tire set. The inability to produce two-wheel lift for a Left-Right steer combination at higher speeds than the other drivers could be viewed as a driver difference, but Driver C was able to achieve two-wheel lift for the Right-Left combination at a minimum initial speed only slightly higher than those of the other drivers. It is believed by the authors that the lack of two-wheel lift may be due to less tire wear for this test set and not due to driver differences. At the point testing was ceased, only eight tests had been conducted on this tire set. All of the other tire sets had more tests conducted on them at the point of two-wheel lift for this steer combination (≥ eleven tests). It would have been interesting to test this hypothesis by conducting more Left-Right tests on this tire set after the completion of the Right-Left tests. If the vehicle did produce two-wheel lift, then this would have provided further evidence for tire wear being a contributing factor to the Bronco II's rollover propensity.

It is interesting to note that except for the first tire set for Driver A, the higher Minimum Initial Speed for the two steer combinations (Left-Right or Right-Left) was dependant upon which steer combination was tested first. This further suggests that tire wear plays an important role in the rollover propensity of the Bronco II.

For the Toyota 4Runner Second Peak values given in Table 7.13, the Left-Right steer tests produced LAR values ranging from 0.71 to 0.76 g with an average of 0.73 g, while the Right-Left steer produced values ranging from 0.74 to 0.78 g with an average of 0.75 g (using only the test sequences that had two-wheel lift). All of the 4Runner LAR values are within 0.03 g of the average values. The 4Runner Left-Right average LAR value is only 0.02 g less than that for the Right-Left steer direction and there is some overlap in the data for these two steer combinations. This is consistent with the results found for the First Peak values. The standard deviation values are relatively low for the Second Peak values (0.022 and 0.023 g), but are higher than those found using First Peak data. This also resulted in higher coefficient of variation values for the Second Peak data (3.0 and -3.1%). Two-wheel lift was not achieved on the Second Peak for 4Runner Tests 055-061 (Driver A) and Tests 105-119 (Driver C), but two-wheel lift did occur on the First Peak for some of the tests in each of these test sets. The maximum Second Peak values are listed for these test ranges, but these values are not used in the calculated statistical results presented at the bottom of the table.

Table 7.13 -- LAR Values Using Second Peak - Driver Comparison for Toyota 4Runner with Larger Tires and Low Fuel

Driver	Left-Right		Right-Left	
	Tests	LAR (g)	Tests	LAR(g)
A	040-042	N.A.	030-038	-0.74
	045-053	0.76	055-061	-0.80*
B	075-081	0.73	067-074	-0.78
C	084-094	0.71	095-102	-0.74
	110-115	0.72	105-109	-0.76*
Average		0.73		-0.75
Std. Dev.		0.022		0.023
Coef. of Var.		3.0%		-3.1%

*- No tests had two-wheel lift on second roll peak - max value listed - not used in calculated statistical results

7.3.3 The Effects of Tire Size on Fishhook Test Results

Fishhook tests were also performed with the 4Runner using the smaller tire size (P225/75R15) that is an option for this vehicle. The initial tests were done with a smaller rim size, but after two tire debeadings the smaller tires were mounted on the rims normally used for the larger tire size (31x10.50R15LT). The results from these tests are given in Tables 7.14 and 7.15. For the Left-Right steering input, the Toyota 4Runner only had two-wheel lift on the First Peak for only one of the two test sequences conducted. For the Right-Left steering inputs, the First Peak LAR values for the small rim and large rim are identical. The LAR value for the Left-Right steering input is very similar to that for the Right-Left steering input.

Table 7.14 -- LAR Values Using First Peak - Toyota 4Runner with Smaller Tires

Driver	Left-Right		Right-Left			
	Large Rim		Small Rim		Large Rim	
	Tests	LAR (g)	Tests	LAR(g)	Tests	LAR (g)
A	268-275	0.68*	248-252	-0.64	260-267	-0.64
	278-285	0.65				

* - No tests had two-wheel lift on the first peak - max value listed

Second Peak LAR values are given in Table 7.15. The two Left-Right sequences produced fairly similar Second Peak LAR values (0.73 and 0.70 g). The Right-Left Second Peak values for the small rim and large rim are 0.05 g different. The Second Peak values for the Left-Right steering combination are very similar to those for the Right-Left combination (considering large rim only).

Table 7.15 -- LAR Values Using Second Peak - Toyota 4Runner with Smaller Tires

Driver	Left-Right		Right-Left			
	Large Rim		Small Rim		Large Rim	
	Tests	LAR (g)	Tests	LAR(g)	Tests	LAR(g)
A	268-275	0.73	248-252	-0.68	260-267	-0.73
	278-285	0.70				

The Minimum Initial Speed Required to Produce Two-Wheel Lift values for the Toyota 4Runner with smaller tires are given in Table 7.16. Based on very limited testing, the Minimum Initial Speed for the Left-Right steer combination appears to be higher than that for the Right-Left combination. This is consistent with the results found with the larger tires.

Table 7.16 -- Minimum Initial Vehicle Speed Required to Produce Two-Wheel Lift - Toyota 4Runner with Smaller Tires

Driver	Left-Right		Right-Left			
	Large Rim		Small Rim		Large Rim	
	Tests	Speed (mph)	Tests	Speed (mph)	Tests	Speed (mph)
A	268-275	34.1*	248-252	34.0	260-267	32.3
	278-285	37.0				

* - No tests had two-wheel lift on the first roll peak - minimum speed for two-wheel lift on second roll peak is listed

The LAR values for the Toyota 4Runner smaller tire and larger tire configurations are compared in Tables 7.17 and 7.18. Driver A was the only driver that performed the smaller tire tests and therefore only the results for Driver A are presented. The results presented in Tables 7.17 and 7.18 show that the tire size did not appear to have an influence on LAR for the limited testing conducted. The smaller tire First Peak LAR values are quite comparable to those found for the larger tire size. The Second Peak LAR values are comparable for the two tire sizes as well. This is consistent with the Tilt Table Ratio results given in Chapter 4 (Table 4.1). Both with and without outriggers, the Tilt Table Ratios for the 4Runner with the smaller tires were the same as those for the larger tires.

Table 7.17 -- LAR Values Using First Roll Peak - Toyota 4Runner Larger versus Smaller Tires

Driver	Left-Right				Right-Left			
	Larger Tires		Smaller Tires		Larger Tires		Smaller Tires	
	Tests	LAR (g)	Tests	LAR (g)	Tests	LAR (g)	Tests	LAR (g)
A	040-042	N.A.	268-275	0.68*	030-038	-0.67	260-267	-0.64
	045-053	0.64	278-285	0.65	055-061	-0.66		

* - No tests had two-wheel lift on the first peak - max value listed

Table 7.18 -- LAR Values Using Second Roll Peak - Toyota 4Runner Larger versus Smaller Tires

Driver	Left-Right				Right-Left			
	Larger Tires		Smaller Tires		Larger Tires		Smaller Tires	
	Tests	LAR (g)	Tests	LAR (g)	Tests	LAR (g)	Tests	LAR (g)
A	040-042	N.A.	268-275	0.73	030-038	-0.74	260-267	-0.73
	045-053	0.76	278-285	0.70	055-061	-0.80*		

*- No tests had two-wheel lift on second roll peak - max value listed

The Minimum Initial Speed Required to Produce Two-Wheel Lift values for the two tire sizes are given in Table 7.19. Very limited testing was conducted, but the Minimum Initial Speed is similar for the two tire sizes.

Table 7.19 -- Minimum Initial Vehicle Speed Required to Produce Two-Wheel Lift - Toyota 4Runner Larger versus Smaller Tires

Driver	Left-Right				Right-Left			
	Larger Tires		Smaller Tires		Larger Tires		Smaller Tires	
	Tests	Speed (mph)	Tests	Speed (mph)	Tests	Speed (mph)	Tests	Speed (mph)
A	040-042	N.A.	268-275	34.1	030-038	35.1	260-267	32.3
	045-053	36.7	278-285	37.0	055-061	34.5		

7.3.4 Fishhook Testing Problems

The Toyota 4Runner is sold with two different tire and rim sizes. The smaller tire on the smaller rim had a tendency to debead during testing. This problem was addressed by mounting the smaller tires on the rim normally used for the larger tires. This helped to reduce the frequency of tire debeading during further testing, although one tire did debead with this configuration also.

The Toyota 4Runner LAR values calculated for first and second roll peaks (after the steering reversal) were quite different.

Tire wear (shoulder wear in particular) appears to be a significant issue in determining whether or not the Bronco II will produce two-wheel lift during the Fishhook maneuver. The shoulder wear produced during testing is not similar to normal wear on a tire seen in real world driving conditions.

The steering stop design used during testing was improved over previous designs, but the drivers still had some tests that resulted in overshooting the steering stop. The use of a steering controller will eliminate these types of problems.

7.3.5 Summary of Fishhook Without Pulse Braking Results

Fishhook testing was performed by three drivers using both the 1990 Toyota 4Runner and 1984 Bronco II. These tests focused on driver repeatability, the influence of fuel level on results, and the effects of tire size.

Three drivers performed repeatability tests with both of the vehicles tested. Driver variability did not seem to influence the results found with the 1990 Toyota 4Runner. The LAR and Minimum Initial Speed Required to Produce Two-Wheel Lift values were very similar for the three drivers. The 1984 Ford Bronco II data were more scattered, but this scatter appears to be more related to tire wear (on the shoulder) issues than it does to driver differences. The shoulder wear produced during testing is not similar to normal wear on a tire seen in real world driving conditions. Based on First Peak data, the LAR coefficient of variation values for the Toyota 4Runner were 2.6 and -1.7% (Left-Right and Right-Left steering inputs respectively), while the Ford Bronco II values were 3.9 and -3.7%. The initial speed required to produce two-wheel lift coefficient of variation values for the 4Runner were 2.0 and 3.4%, while the Bronco II values were 9.4 and 5.2%.

One driver performed tests with a smaller tire size (P225/75R15) that is an option for the Toyota 4Runner. Comparing the results from the small tire tests to those performed with the larger tire size

(31x10.50R15LT) showed that tire size did not have a large influence on results. The LAR and initial speed required to produce two-wheel lift values were very similar for the two tire sizes. This is consistent with the Tilt Table Ratio results given in Chapter 4.

The steering stop design used during testing was improved over previous designs, but the drivers still had some tests that resulted in overshooting the steering stop. The use of a steering controller will eliminate these types of problems.

7.4 Fishhook with Pulse Braking Maneuver Test Results and Analysis - Driver Effects

Fishhook with Pulse Braking tests were performed by three drivers. The results from these tests are presented below. Driver effects are examined and a general assessment of the Fishhook with Pulse Braking maneuver is given.

7.4.1 Fishhook with Pulse Braking Tests Performed for Each Vehicle

The Fishhook with Pulse Braking maneuver is fairly similar to the J-Turn with Pulse Braking maneuver except that the steering profile is a Fishhook instead of a J-Turn. The pulse braking application causes the same decrease in side-force capabilities for the tires as it did in the J-Turn with Pulse Braking maneuver. This decrease in side-force capabilities results in similar decreases in vehicle responses followed by large increases in vehicle responses for both of these maneuvers.

Fishhook with Pulse Braking was performed by three drivers using the 1984 Bronco II. The results presented in this chapter focus on driver differences. A comparison of the results of this maneuver to those for the Fishhook without Pulse Braking and the J-Turn with Pulse Braking maneuvers is presented in Chapter 11 - Determination and Selection of Phase II Test Maneuvers. The effects of pulse braking in general are more closely examined in Chapter 10 - Steering Controller Test Results and Analysis.

The baseline test results are given in Table 7.20. The Driver, Steering Input, Test No., Initial Speed, Handwheel Angle, Pulse Brake Magnitude and Duration, Peak Roll Angle Pre-Pulse, Dip, and Post Pulse, Peak Corrected Lateral Acceleration Pre-Pulse, Dip, and Post-Pulse, and Amount of Two-Wheel Lift values are given. Driver A performed three sets of tests, while Drivers B and C performed one set each.

The initial handwheel angle was set at 270 degrees and was controlled with a steering stop. The Handwheel Angle listed in Table 7.20 is the second steering input magnitude that occurs when the pulse brake is applied. The value listed for each test is averaged over a 0.40 second range. The second steering input was not controlled with a steering stop and therefore is quite variable. This variability would be dramatically reduced with the use of a steering controller. As seen in Table 7.20, the Peak Post-Pulse values are generally larger than the Pre-Pulse values. The higher brake force magnitudes generally result in higher differences between the Pre- and Post-Pulse values. This is consistent with the J-Turn with Pulse Braking results presented in Section 7.2. The relationship between Pulse Magnitude and Pre- and Post-Pulse values is further studied in Chapter 10. All three drivers were able to achieve two-wheel lift in both the Right-Left and Left-Right steering combinations.

Table 7.20 -- Fishhook with Pulse Braking Test Results - Ford Bronco II

Driver	Steering Input	Test No.	Initial Speed (mph)	Hand-wheel Angle (deg)	Pulse Brake Magnitude (lbf)	Pulse Brake Duration (sec)	Peak Roll Angle Pre-Pulse (deg)	Roll Angle Dip due to Pulse (deg)	Peak Roll Angle Post-Pulse (deg)	Peak Cor. Lat. Acc. Pre-Pulse (g)	Cor. Lat. Acc. Dip due to Pulse (g)	Peak Cor. Lat. Acc. Post-Pulse (g)	Amount of Two-Wheel Lift
A	L-R	141	37.1	397	101	0.29	-7.1	-1.9	-7.8	0.76	0.38	0.78	None
	L-R	142	38.1	397	150	0.33	-7.6	-1.0	-12.2	0.63	0.26	0.91	Moderate
	L-R	143	38.1	358	127	0.27	-7.9	-2.6	-8.6	0.63	0.39	0.81	None
	L-R	144	38.5	356	113	0.34	-7.7	-3.4	-6.8	0.69	0.47	0.72	None
	L-R	145	38.1	388	168	0.30	-8.0	0.0	-18.0	0.60	0.25	1.03	Major
	R-L	146	37.8	-510	106	0.29	7.2	1.5	8.4	-0.75	-0.37	-0.77	None
	R-L	147	37.3	-390	132	0.36	6.8	2.6	7.7	-0.75	-0.42	-0.76	None
	R-L	148	39.0	-312	139	0.47	7.3	-0.3	13.0	-0.68	-0.22	-0.94	Moderate
	R-L	150	39.1	-306	171	0.41	7.2	-0.3	18.5	-0.69	-0.26	-1.00	Major
	R-L	151	37.7	-360	122	0.38	7.1	2.2	8.3	-0.74	-0.37	-0.76	None
	R-L	152	37.4	-381	135	0.40	7.3	1.7	9.2	-0.78	-0.38	-0.78	None
A	L-R	222	35.7	429	158	0.30	-7.0	-1.9	-7.3	0.76	0.36	0.73	None
	L-R	223	36.1	418	155	0.31	-7.3	-2.9	-6.7	0.75	0.39	0.70	None
	L-R	224	38.3	389	136	0.37	-8.1	-4.4	-7.1	0.72	0.52	0.72	None
	L-R	225	38.8	368	185	0.35	-7.9	-0.9	-16.3	0.69	0.30	0.89	Major
	L-R	226	37.9	366	185	0.34	-7.7	-0.9	-18.3	0.73	0.28	0.95	Major
	L-R	227	36.7	371	181	0.30	-7.6	-1.6	-9.5	0.71	0.31	0.83	Moderate
	L-R	228	37.3	375	175	0.32	-7.7	-1.4	-15.3	0.69	0.35	0.85	Major
	R-L	230	34.9	-350	153	0.36	6.5	1.8	7.8	-0.70	-0.36	-0.69	None
	R-L	231	35.8	-358	166	0.38	6.5	0.8	8.7	-0.71	-0.29	-0.73	None
	R-L	232	36.3	-367	132	0.36	6.7	2.8	7.3	-0.74	-0.44	-0.71	None
	R-L	233	36.2	-383	152	0.38	7.2	2.0	10.0	-0.70	-0.30	-0.72	None
	R-L	234	38.9	-345	171	0.38	7.3	0.6	17.9	-0.69	-0.30	-0.95	Major
	R-L	235	37.9	-343	154	0.38	7.6	2.9	13.6	-0.64	-0.31	-0.82	Moderate
	R-L	236	36.5	-384	147	0.39	6.9	2.7	7.9	-0.67	-0.35	-0.69	None
	R-L	237	37.8	-341	172	0.36	7.1	1.6	11.4	-0.64	-0.31	-0.80	Moderate

Table 7.20 -- Fishhook with Pulse Braking Test Results - Ford Bronco II (continued)

Driver	Steering Input	Test No.	Initial Speed (mph)	Hand-wheel Angle (deg)	Pulse Brake Magnitude (lbf)	Pulse Brake Duration (sec)	Peak Roll Angle Pre-Pulse (deg)	Roll Angle Dip due to Pulse (deg)	Peak Roll Angle Post-Pulse (deg)	Peak Cor. Lat. Acc. Pre-Pulse (g)	Cor. Lat. Acc. Dip due to Pulse (g)	Peak Cor. Lat. Acc. Post-Pulse (g)	Amount of Two-Wheel Lift
A	R-L	240	35.4	-516	148	0.37	6.3	0.1	8.8	-0.71	-0.18	-0.70	None
	R-L	241	36.1	-426	142	0.35	6.3	-0.7	9.4	-0.73	-0.16	-0.81	None
	R-L	242	36.6	-590	151	0.35	6.6	0.3	8.7	-0.71	-0.20	-0.69	None
	R-L	243	38.3	-640	130	0.29	7.2	0.2	9.8	-0.73	-0.25	-0.74	None
	R-L	244	37.3	-487	116	0.32	6.6	0.2	10.1	-0.76	-0.22	-0.77	Moderate
	R-L	245	38.5	-433	161	0.38	7.3	0.4	10.5	-0.65	-0.21	-0.96	Minor
	R-L	246	39.1	-392	156	0.37	6.9	0.2	11.5	-0.65	-0.25	-1.04	Moderate
	R-L	247	38.7	-371	138	0.35	6.9	0.4	10.8	-0.73	-0.24	-0.93	Moderate
	L-R	248	35.8	385	74	0.32	-7.3	-3.1	-6.9	0.79	0.52	0.75	None
	L-R	249	36.4	382	148	0.27	-7.4	-2.6	-7.2	0.79	0.42	0.75	None
	L-R	250	37.3	378	136	0.32	-7.4	-1.2	-9.0	0.74	0.33	0.81	None
	L-R	251	37.7	402	163	0.30	-7.6	-0.7	-10.3	0.74	0.27	0.86	Moderate
	L-R	252	39.6	356	138	0.27	-7.8	-1.3	-10.1	0.71	0.36	0.86	Moderate
	L-R	253	38.4	393	135	0.29	-7.9	-1.2	-10.2	0.72	0.33	0.84	Moderate
	L-R	254	37.1	380	119	0.30	-7.4	-2.2	-8.1	0.78	0.40	0.76	None
	L-R	255	38.2	398	136	0.35	-7.5	-0.4	-10.5	0.69	0.24	0.85	Moderate

Table 7.20 -- Fishhook with Pulse Braking Test Results - Ford Bronco II (continued)

Driver	Steering Input	Test No.	Initial Speed (mph)	Hand-wheel Angle (deg)	Pulse Brake Magnitude (lbf)	Pulse Brake Duration (sec)	Peak Roll Angle Pre-Pulse (deg)	Roll Angle Dip due to Pulse (deg)	Peak Roll Angle Post-Pulse (deg)	Peak Cor. Lat. Acc. Pre-Pulse (g)	Cor. Lat. Acc. Dip due to Pulse (g)	Peak Cor. Lat. Acc. Post-Pulse (g)	Amount of Two-Wheel Lift
B	R-L	203	35.4	-332	77	0.58	7.1	1.1	8.1	-0.62	-0.28	-0.77	None
	R-L	204	35.6	-347	96	0.60	6.1	0.2	9.6	-0.54	-0.19	-0.82	None
	R-L	205	36.9	-297	119	0.38	7.0	1.0	9.4	-0.65	-0.31	-0.81	None
	R-L	206	37.4	-336	133	0.60	6.9	-0.6	10.9	-0.63	-0.17	-0.92	Moderate
	R-L	208	36.6	-344	63	0.89	6.4	1.3	9.4	-0.56	-0.34	-0.74	None
	R-L	209	37.1	-371	86	0.85	7.4	-0.1	12.2	-0.67	-0.28	-0.94	Moderate
	R-L	211	37.1	-319	127	0.37	6.8	2.8	8.8	-0.65	-0.39	-0.79	None
	R-L	212	37.5	-308	183	0.48	6.7	-0.6	11.9	-0.64	-0.18	-0.95	Moderate
	L-R	213	33.9	250	110	0.35	-6.4	-4.1	-6.5	0.65	0.50	0.70	None
	L-R	214	35.3	305	122	0.46	-7.3	0.6	-12.3	0.70	0.23	1.08	Moderate
	L-R	215	35.8	262	124	0.45	-6.7	0.2	-10.2	0.68	0.22	0.99	Moderate
	L-R	217	36.0	309	106	0.43	-6.9	-0.0	-11.8	0.68	0.25	1.00	Moderate
	L-R	218	36.0	354	86	0.57	-7.2	0.1	-11.7	0.71	0.27	1.03	Moderate

Table 7.20 -- Fishhook with Pulse Braking Test Results - Ford Bronco II (continued)

Driver	Steering Input	Test No.	Initial Speed (mph)	Hand-wheel Angle (deg)	Pulse Brake Magnitude (lbf)	Pulse Brake Duration (sec)	Peak Roll Angle Pre-Pulse (deg)	Roll Angle Dip due to Pulse (deg)	Peak Roll Angle Post-Pulse (deg)	Peak Cor. Lat. Acc. Pre-Pulse (g)	Cor. Lat. Acc. Dip due to Pulse (g)	Peak Cor. Lat. Acc. Post-Pulse (g)	Amount of Two-Wheel Lift
C	R-L	366	34.9	-418	156	0.74	3.2	-0.4	19.4	-0.72	-0.24	-0.64	None
	R-L	368	37.5	-409	232	0.81	6.2	0.6	7.5	-0.65	-0.25	-0.75	None
	R-L	369	38.2	-415	246	0.40	6.7	-0.7	12.6	-0.67	-0.26	-0.97	Minor
	R-L	371	37.5	-231	228	0.61	3.8	-0.2	5.9	-0.49	-0.07	-0.63	None
	R-L	372	36.9	-394	215	0.44	6.3	-0.5	17.6	-0.67	-0.22	-1.05	Moderate
	R-L	373	36.6	-344	257	0.49	6.3	0.4	11.2	-0.65	-0.20	-0.94	Moderate
	R-L	374	35.8	-314	185	0.35	6.0	0.1	10.6	-0.63	-0.22	-0.92	Moderate
	R-L	375	34.6	-354	183	0.36	6.3	-0.7	11.8	-0.64	-0.22	-0.94	Moderate
	R-L	376	32.0	-392	257	0.43	5.8	-0.6	10.4	-0.63	-0.15	-0.89	Moderate
	L-R	377	34.9	329	199	0.37	-6.2	1.6	-11.0	0.66	0.20	0.96	Moderate
	L-R	378	33.6	393	209	0.34	-6.4	1.4	-11.9	0.64	0.20	0.98	Moderate
	L-R	379	33.1	341	263	0.39	-6.1	1.5	-11.7	0.60	0.12	1.00	Moderate
	L-R	380	30.8	364	203	0.38	-5.7	1.1	-9.7	0.57	0.17	0.90	Moderate
	L-R	381	30.2	441	235	0.44	-5.6	1.3	-10.7	0.58	0.10	0.91	Moderate
	L-R	382	29.2	420	258	0.39	-5.8	1.0	-9.7	0.59	0.12	0.92	Moderate
	L-R	383	26.7	507	135	0.61	-5.5	-0.1	-5.3	0.60	0.14	0.59	None
	L-R	385	27.0	582	166	0.43	-5.4	0.7	-8.3	0.57	0.15	0.79	None
	L-R	386	27.4	526	203	0.49	-4.6	0.7	-8.7	0.52	0.11	0.80	None
	L-R	387	28.4	566	199	0.36	-5.7	0.6	-9.7	0.60	0.16	0.86	Moderate

7.4.2 Fishhook with Pulse Braking and Rollover Propensity

From Phase I-A testing, it did not appear that the Fishhook with Pulse Braking maneuver gives any greater indication of rollover propensity than the combination of the Fishhook without Pulse Braking and the J-Turn with Pulse Braking.

The Fishhook with Pulse Braking maneuver has even more primary input variables than the J-Turn with Pulse Braking maneuver. All of these inputs create a more difficult maneuver for the driver to perform. A steering controller would help reduce the demands on the driver. The factors that create the variability seen in the J-Turn with Pulse Braking and the Fishhook without Pulse Braking maneuvers are present with this maneuver.

Although there are many complexities with the Fishhook with Pulse Braking maneuver, it was recommended that this maneuver be further evaluated in Phase I-B of NHTSA's Light Vehicle Dynamic Rollover Research program. In the following section, driver variability effects on the repeatability of the Fishhook with Pulse Braking maneuver are examined.

7.4.3 Driver Variability Effects on the Repeatability of the Fishhook with Pulse Braking Maneuver

The Average, Minimum, and Maximum Pulse Brake Magnitude, Pulse Brake Duration and Handwheel Input (handwheel angle at pulse-brake application) for each driver are given in Table 7.21.

The Average Pulse Brake Magnitudes are very different for the three drivers. These values ranged from 110 pounds-force for Driver B to 212 pounds-force for Driver C. Drivers A and B had a similar range of values. The Minimum and Maximum values for Driver C are much higher than those for the other drivers. Drivers A and C also conducted J-Turn with Pulse Braking tests. Driver A had lower Average values than Driver C for these tests also (165 and 244 pounds-force respectively).

Table 7.21 -- Average and Range of Values for Driver Controlled Inputs for the Fishhook with Pulse Braking Maneuver

Driver	Pulse Brake Magnitude (lbf)			Pulse Brake Duration (sec)			Handwheel Input (deg)		
	Average	Min	Max	Average	Min	Max	Average	Min	Max
A	145	74	185	0.34	0.27	0.47	397	306	640
B	110	63	183	0.54	0.35	0.89	318	250	371
C	212	135	263	0.46	0.34	0.81	407	231	582

The Average Pulse Brake Durations for each driver are quite different also. Driver A had the lowest Average (0.34 seconds) and the lowest range of values. Driver B tended to have a much longer Pulse Brake Duration (0.54 seconds on average). Driver C had a similar range of values as Driver B, but on Average had a Pulse Brake Duration between that for Driver A and Driver B (0.46 seconds). The results for Drivers A and C are consistent with what was found in the J-Turn with Pulse Braking tests. Driver A had an Average Pulse Brake Duration of 0.36 seconds while Driver C had an average of 0.45 seconds in the J-Turn with Pulse Braking tests.

The Average Handwheel Inputs for Drivers A and C are fairly similar (approximately 400 degrees). Driver B had a lower Average Handwheel Input than the other drivers (318 degrees). The large Average Handwheel Input difference between Driver B and the other drivers may not be important because the Peak Corrected Lateral Acceleration Pre-Pulse values are relatively high for all three drivers. Even though Driver B had the lowest Average Handwheel Input, his Average Peak Corrected Lateral Acceleration Pre-Pulse fell between those for Drivers A and C (0.71 g - A, 0.64 g - B, 0.61 g - C). The handwheel input could be better controlled with a better steering stop system or with the use of a steering controller.

Despite the difference in driver inputs, all three drivers were able to achieve two-wheel lift in both steering directions for the Bronco II. As will be shown next, they also produced similar LAR values.

There were some differences between the Minimum Initial Speed Required to Produce Two-Wheel Lift for the drivers.

The LAR values for each combination of driver, steering direction, and test set are given in Table 7.22. The Left-Right tests had LAR values ranging from 0.78 to 0.86 g with Drivers B and C's values falling within the range of that for Driver A. The Right-Left tests had a slightly larger range with LAR values ranging from -0.76 to -0.87 g. Driver B's LAR value is only slightly above the range found for Driver A, while Driver C's value is within the range.

Table 7.22 -- Fishhook with Pulse Braking LAR Values - Driver Comparison for Bronco II Tests

Driver	Left-Right		Right-Left	
	Tests	LAR (g)	Tests	LAR (g)
A	141-145	0.86	146-152	-0.86
	222-228	0.78	230-237	-0.76
	248-255	0.83	240-247	-0.79
B	213-218	0.85	203-212	-0.87
C	377-387	0.83	366-376	-0.82
Average		0.83		-0.82
Standard Deviation		0.031		0.046
Coef. of Variation (%)		3.7%		-5.7%

The average LAR values given in Table 7.22 are very similar in magnitude for the two steering inputs (0.83 and -0.82 g). The standard deviation values are 0.031 for Left-Right steering inputs and 0.046 g for Right-Left steering inputs. This yields coefficient of variation values of 3.7 and 5.7 percent respectively.

The Minimum Initial Speed Required to Produce Two-Wheel Lift for each Fishhook with Pulse Braking test sequence is listed in Table 7.23. Drivers A and B have very similar Minimum Initial Speed values, while Driver C has values that are much lower. Examining the driver inputs listed in Table 7.21 suggests that main explanation for the lower values for Driver C is his higher Pulse Brake Magnitude. Driver C had very similar Handwheel Input values to those for Driver A and his Pulse Brake Duration was in between those for the other two drivers on average. These two facts suggest that Driver C's higher Pulse Brake Magnitude is the most likely explanation for his lower Minimum Initial Speed values.

Table 7.23 -- Fishhook with Pulse Brake Minimum Initial Speed Required to Produce Two-Wheel Lift - Driver Comparison for Bronco II Tests

Driver	Minimum Initial Vehicle Speed (mph)			
	Left-Right		Right-Left	
	Tests	Speed (mph)	Tests	Speed (mph)
A	141-145	38.2	146-152	39.0
	222-228	36.7	230-237	37.8
	248-255	37.7	240-247	37.3
B	213-218	37.1	203-212	35.2
C	377-387	28.4	366-376	32.0

Even though there were driver differences, all of the drivers were able to produce two-wheel lift in both directions for the Bronco II using the Fishhook with Pulse Braking maneuver. Comparisons of Fishhook with Pulse Braking results to J-Turn with Pulse Braking and Fishhook without Pulse Braking results are presented in Chapter 11 - Development of the Phase II Test Matrix.

<u>7.4.4 Summary of Fishhook with Pulse Braking Results</u>

The Fishhook with Pulse Braking maneuver is fairly similar to the J-Turn with Pulse Braking maneuver except that the steering profile is a Fishhook instead of a J-Turn. The pulse braking application causes the same decrease in side-force capabilities for the tires as it did in the J-Turn with Pulse Braking maneuver. This decrease in side-force capabilities results in similar decreases in vehicle responses followed by large increases in vehicle responses for both of these maneuvers.

Fishhook with Pulse Braking was performed by three drivers using the 1984 Bronco II. Driver A performed three sets of tests, while Drivers B and C performed one set each. The initial handwheel angle was set at 270 degrees and was controlled with a steering stop. The second steering input was not controlled with a steering stop and therefore is quite variable. This variability could be dramatically reduced with the use of a steering controller.

The Peak Post-Pulse values are generally larger than the Pre-Pulse values. Higher brake force magnitudes generally result in higher differences between the Pre- and Post-Pulse values.

The Left-Right tests had LAR values ranging from 0.78 to 0.86 g with Drivers B and C's values falling within the range of that for Driver A. The Right-Left tests had a slightly larger range with LAR values ranging from -0.76 to -0.87 g. Driver B's LAR value is only slightly larger than the range found for Driver A, while Driver C's value is within the range. The Average LAR values are very similar in magnitude for the two steering inputs (0.83 and -0.82 g).

Drivers A and B had very similar Minimum Initial Speed Required to Produce Two Wheel Lift values, while Driver C had values that were much lower. An examination of the driver inputs suggests that the main explanation for the lower values for Driver C is his higher Pulse Brake Magnitude.

Even though there were driver differences, all of the drivers were able to produce two-wheel lift in both directions for the Bronco II using the Fishhook with Pulse Braking maneuver. Comparisons of Fishhook with Pulse Braking results to J-Turn with Pulse Braking and Fishhook without Pulse Braking results are presented in Chapter 11.

7.5 Summary of Driver Variability Effects on Test Results

Driver variability effects on test results were evaluated using four test maneuvers: J-Turn (Without Pulse Braking), J-Turn with Pulse Braking, Fishhook Without Pulse Braking, and Fishhook with Pulse Braking.

Two drivers performed J-Turn tests with the Toyota 4Runner. In general, increasing J-Turn severity, by increasing steering magnitude or vehicle speed, resulted in increasing lateral acceleration and roll angle up to the point of limit response. For the Toyota 4Runner, the limit response during the J-Turn testing was two-wheel lift. Both drivers were able to produce two-wheel lift in both the Left and Right steer directions.

The J-Turn maneuver was found to be fairly repeatable. For all groups of repeatability tests (similar speed, handwheel inputs, and throttle), the resulting maximum lateral accelerations and maximum roll angles were very similar. Throttle position did appear to make a large difference in test results. To reduce the amount of variability in testing, the drivers will release the throttle in Phase II research upon the initiation of the steering input.

The J-Turn maneuver is a simple test to conduct relative to other vehicle rollover propensity tests. It appears to induce two-wheel lift for some vehicles. The initial test speed appears to be a measure that can be used to quantify a vehicle's rollover propensity. For the above reasons, the J-Turn maneuver is a good candidate for use in a potential dynamic rollover propensity test procedure.

Two drivers conducted a limited number of J-Turn with Pulse Braking tests with the 1984 Ford Bronco II. Driver A completed two sets of tests for each steering direction while Driver C completed one set.

Driver A generally had a larger Peak Handwheel Rate than Driver C. Driver C generally had a larger Pulse Brake Magnitude and Duration. While these differences produced test-to-test variations, the overall test results for each driver were fairly similar. Driver A and Driver C had Minimum Initial Speeds Required to Produce Two-Wheel Lift that were in the same range (36 to 42 mph for all combinations of steering direction and replication). The LAR values for each combination of steering direction, driver, and test set are very similar as well (0.86 to 0.87 g for Right steer and -0.82 to -0.85 g for Left steer).

LAR values were much less variable than the Minimum Lateral Accelerations Required to Produce Two-Wheel Lift. This suggests that having multiple instances of no two-wheel lift and two-wheel lift tests and then taking the average of the minimum lateral acceleration for the two-wheel lift cases and the maximum lateral acceleration for the no two-wheel lift cases (calculation of an LAR) helps to "filter" the test results and produce a fairly consistent answer.

The J-Turn With Pulse Braking maneuver is expected to induce two-wheel lift for many vehicles. The initial test speed appears to be a measure that can be used to quantify a vehicle's rollover propensity.

Fishhook testing was performed by three drivers using both the 1990 Toyota 4Runner and 1984 Bronco II. These tests focused on driver repeatability, the influence of fuel level on results, and the effect of tire size.

Three drivers performed repeatability tests with both of the vehicles tested. Driver variability did not seem to influence the results found with the 1990 Toyota 4Runner. The LAR and Minimum Initial Speed Required to Produce Two-Wheel Lift values were very similar for the three drivers. The 1984 Ford Bronco II data were more scattered, but this scatter appears to be more related to tire wear (on the shoulder) issues than it does to driver differences. The shoulder wear produced during testing is not similar to normal wear on a tire seen in real world driving conditions. Based on First Peak data, the LAR coefficient of variation values for the Toyota 4Runner were 2.6 and -1.7% (Left-Right and Right-Left steering inputs respectively), while the Ford Bronco II values were 3.9 and -3.7%. The initial speed required to produce two-wheel lift coefficient of variation values for the 4Runner were 2.0 and 3.4%, while the Bronco II values were 9.4 and 5.2%.

One driver performed tests with a smaller tire size (P225/75R15) that is an option for the Toyota 4Runner. Comparing the results from the small tire tests to those performed with the larger tire size (31x10.50R15LT) showed that tire size did not have a large influence on results. The LAR and initial speed required to produce two-wheel lift values were very similar for the two tire sizes. This is consistent with the Tilt Table Ratio results given in Chapter 4.

The steering stop design used during testing was improved over previous designs, but the drivers still had some tests that resulted in overshooting the steering stop. The use of a steering controller will eliminate these types of problems.

The Fishhook with Pulse Braking maneuver is fairly similar to the J-Turn with Pulse Braking maneuver except that the steering profile is a Fishhook instead of a J-Turn. The pulse braking application causes the same decrease in side-force capabilities for the tires as it did in the J-Turn with Pulse Braking maneuver. This decrease in side-force capabilities results in a similar decreases in vehicle responses followed by large increases in vehicle responses for both of these maneuvers.

Fishhook with Pulse Braking was performed by three drivers using the 1984 Bronco II. Driver A performed three sets of tests, while Drivers B and C performed one set each. The initial handwheel angle was set at 270 degrees and was controlled with a steering stop. The second steering input was not controlled with a steering stop and therefore is quite variable. This variability could be dramatically reduced with the use a steering controller.

The Peak Post-Pulse values are generally larger than the Pre-Pulse values. Higher brake force magnitudes generally result in higher differences between the Pre- and Post-Pulse values.

The Left-Right tests had LAR values ranging from 0.78 to 0.86 g with Drivers B and C's values falling within the range of that for Driver A. The Right-Left tests had a slightly larger range with LAR values ranging from -0.76 to -0.87 g. Driver B's LAR value is only slightly larger than the range found for Driver A, while Driver C's value is within the range. The Average LAR values are very similar in magnitude for the two steering inputs (0.83 and -0.82 g).

Drivers A and B had very similar Minimum Initial Speed Required to Produce Two Wheel Lift values, while Driver C had values that were much lower. An examination of the driver inputs suggests that main explanation for the lower values for Driver C is his higher Pulse Brake Magnitude.

Even though there were driver differences, all of the drivers were able to produce two-wheel lift in both directions for the Bronco II using the Fishhook with Pulse Braking maneuver. Comparisons of Fishhook with Pulse Braking results to J-Turn with Pulse Braking and Fishhook without Pulse Braking results are presented in Chapter 11.

8.0 TESTING PERFORMED TO DETERMINE OUTRIGGER EFFECTS RESULTS AND ANALYSIS

Outrigger effects were studied using three different maneuvers: the Fishhook Without Pulse Braking, the Fishhook With Pulse Braking, and Sinusoidal Sweep. The results for each of these maneuvers will be discussed below. Up to three outrigger conditions were evaluated with each maneuver: ballasted outriggers, normal outriggers (unballasted), and/or no outriggers. Ballasted outriggers were created by placing sandbag weights on the normal outriggers. A total of 100 lbs was added to each outrigger. This allowed the simulation of a heavier outrigger compared to the normal outriggers used in this research. The effect of the extra weight on roll, yaw, and pitch moment of inertia of the ballast is given in Section 6.2.1.

8.1 Fishhook Without Pulse Braking Maneuver and Outrigger Effects

The LAR values for the Ballasted outrigger tests are given in Tables 8.1 and 8.2. Individual test results are given in Appendix A. The Unballasted LAR values are given for comparison purposes. Driver C performed tests with ballasted outriggers on the Toyota 4Runner, while Driver A performed tests with ballasted outriggers on the Bronco II. For both First and Second peak values, the Ballasted outrigger Left-Right LAR values for Driver C/4Runner (0.63 and 0.71 g respectively) fall within the range for those found with Unballasted outriggers (0.62 to 0.66 g and 0.71 to 0.72 g). The Right-Left steer combination for Driver C/4Runner had slightly lower First and Second Peak LAR values for the Ballasted condition (-0.60 g vs. -0.64 to -0.66 g and -0.72 g vs.-0.74 to -0.76 g). The Left-Right Ballasted outrigger LAR value for Driver A/Bronco II (0.73 g) was slightly lower than the range for Unballasted tests (0.75 to 0.78 g). The Right-Left Ballasted outrigger LAR value for Driver A/Bronco II (-0.70 g) was at the low end of the range for Unballasted tests (-0.70 to -0.72 g). More test sequences would have to be performed to make a more definitive statement, but the ballast added to the outriggers did not appear to have a strong effect on the calculated LAR values, producing only slightly lower LAR values for the limited number of tests sequences conducted.

Table 8.1 -- LAR Values Using First Peak - Outrigger Comparison for the Bronco II and the Toyota 4Runner with Larger Tires

Driver / Vehicle	Left-Right				Right-Left			
	Unballasted		Ballasted		Unballasted		Ballasted	
	Tests	LAR (g)	Tests	LAR (g)	Tests	LAR (g)	Tests	LAR (g)
C / Toyota 4Runner	084-094 110-115	0.66 0.62	141-149	0.63	095-102 105-109	-0.64 -0.66	133-140	-0.60
A / Bronco II	003-013 043-050 258-268	0.78 0.76 0.75	053-063	0.73	014-026 029-042 269-276	-0.70 -0.71 -0.72	064-076	-0.70

Table 8.2 -- LAR Values Using Second Peak - Outrigger Comparison for Toyota 4Runner with Larger Tires

Driver	Left-Right				Right-Left			
	Unballasted		Ballasted		Unballasted		Ballasted	
	Tests	LAR (g)	Tests	LAR (g)	Tests	LAR (g)	Tests	LAR (g)
C	084-094 110-115	0.71 0.72	141-149	0.71	095-102 105-109	-0.74 -0.76*	133-140	-0.72

* - No tests had two wheel lift - max value listed

The Minimum Initial Speed Required to Produce Two-Wheel Lift values are given in Table 8.3. Most of the Minimum Initial Speed values for the Ballasted tests fall within the range of those for the Unballasted tests. The only exception to this is the Right-Left Driver A/Bronco II Ballasted outrigger value (44.6 mph) which is only 1 mph above the range of values for the corresponding Unballasted outrigger values (40.2 to 43.6 mph).

Table 8.3 -- Minimum Initial Speed Required to Produce Two-Wheel Lift - Outrigger Comparison for the Bronco II and the Toyota 4Runner with Larger Tires

Driver / Vehicle	Left-Right				Right-Left			
	Unballasted		Ballasted		Unballasted		Ballasted	
	Tests	Speed (mph)	Tests	Speed (mph)	Tests	Speed (mph)	Tests	Speed (mph)
C / Toyota 4Runner	084-094 110-115	37.8 36.2	141-149	36.7	095-102 105-109	32.5 35.0	133-140	33.6
A / Bronco II	003-013 043-050 258-268	39.1 38.4 46.6	053-063	44.0	014-026 029-042 269-276	43.6 42.0 40.2	064-076	44.6

The intention of this testing was to try and determine what the LAR and Minimum Speed Required to Produce Two-Wheel Lift might be if the testing was performed with no outriggers. Inertial parameters for the Ford Bronco II with no outriggers, Normal outriggers, and Ballasted outriggers were presented in Table 6.3. Similar values for the Toyota 4Runner were not available. The results presented in Table 6.3 show how the roll inertia of the vehicle increased with increasing outrigger weight. The "average" Bronco II LAR values for the Normal outrigger and Ballasted outrigger cases were linearly interpolated as a function of vehicle roll inertia to determine what the LAR might be with no outriggers. The results of this interpolation are displayed in Figure 8.1. The range of values for the Normal outrigger case are shown, while single points are shown for the Ballasted outrigger case (only one sample) and for the linearly interpolated value for "no outriggers". The results presented in Figure 8.1 suggest that the LAR would increase slightly if no outriggers were present. The effect on the Left-Right steer combination appears to be greater than it is for the Right-Left steer combination. It is not clear that the assumption of a linear relationship between LAR and the roll inertia of the vehicle is appropriate. Also, the "average" values used to determine the LAR had as few as one sample and only as many as three samples. Further testing would be required to prove the results suggested from this analysis.

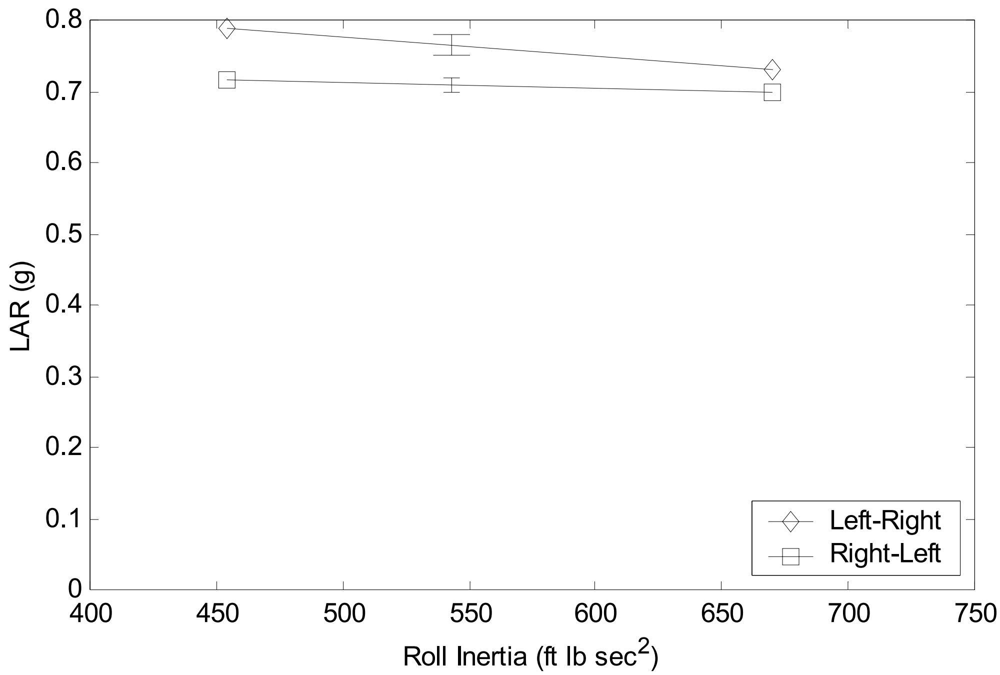


Figure 8.1 -- LAR as a Function of Vehicle Roll Inertia for the Ford Bronco II - Linear Interpolation

The Minimum Speed Required to Produce Two-Wheel Lift for the Bronco II Normal and Ballasted outrigger cases were also linearly interpolated to determine what the value would be if no outriggers were present. The results are presented in Figure 8.2. The results presented in Figure 8.2 suggest that the Minimum Speed Required to Produce Two-Wheel Lift would decrease slightly if no outriggers were present. These results are somewhat counter-intuitive, but given that the decreasing trend is only slight, the lack of significant amounts of data may be the reason for this result. In fact the range of values for the Speed Required to Produce Two-Wheel Lift (Normal outrigger case) is much larger than that found in Figure 8.1 for LAR. More rigorous testing may show that the trend is the opposite of that shown in Figure 8.2 .

Due to time constraints, very limited testing was performed to examine the true effect that the outriggers have on Fishhook maneuver results. Further testing in this area will be conducted in later phases of this research.

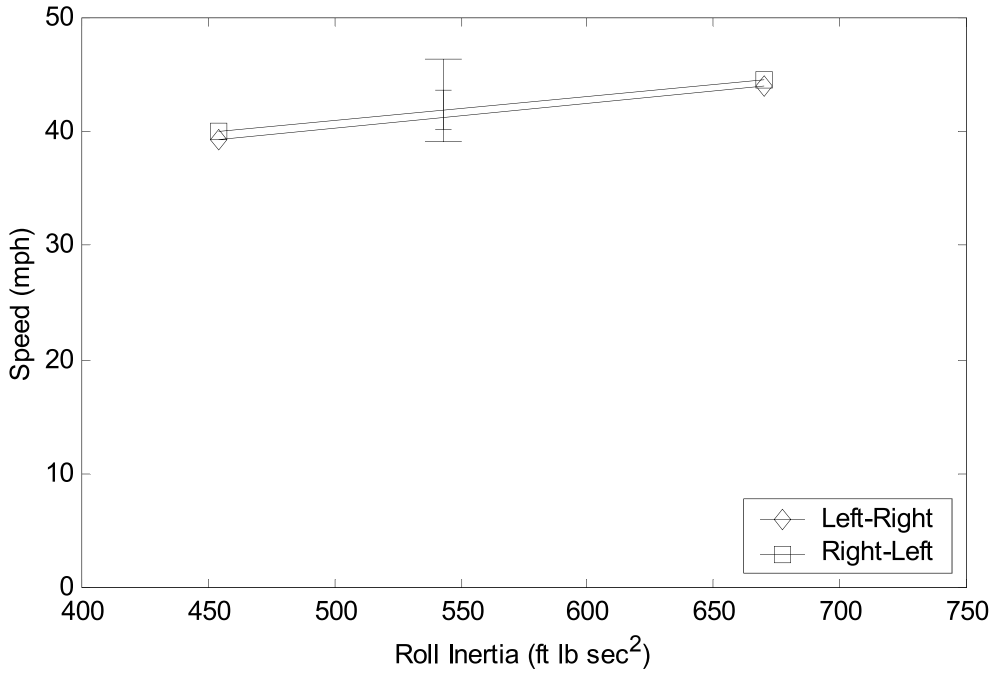


Figure 8.2 -- Minimum Speed Required to Produce Two-Wheel Lift as a Function of Vehicle Roll Inertia for the Ford Bronco II - Linear Interpolation

The handwheel angle transducer/data acquisition for the Ballasted Driver C/Toyota 4Runner tests was not operating properly and therefore no direct comparison of individual Ballasted and Unballasted tests can be made. The results of several Ballasted and Unballasted Driver A/Bronco II tests are given in Table 8.4. Two sets of "matched" tests are given. The first set has a nominal speed of 37.7 mph and the second 44.4 mph. The First Peak Handwheel Angles are very similar because they were controlled with a steering stop. The Second Peaks are somewhat variable, but are at a high enough angle that the tire lateral acceleration capability is saturated.

For both the first and second set of tests listed in Table 8.4, the First and Second Peak Lateral Accelerations for the Ballasted and Unballasted outriggers have similar values. For the 37.7 mph tests, the First Peak Roll Angle values are similar for the Ballasted and Unballasted outriggers, but the Second Peak Roll Angles for the Ballasted outriggers are somewhat lower than those for the Unballasted outriggers. For the 44.4 mph tests, the First Peak Roll Angles are somewhat larger for the Ballasted outriggers. The Second Peak Roll Angle values have some overlap in value for the two outrigger conditions.

For both sets of tests, the First Roll Rate Peak values are similar for the two outrigger conditions. The Second Roll Rate Peak values are generally lower for the Ballasted outriggers. This is not surprising since the Ballasted outriggers add a great deal of inertia in the roll plane. It is somewhat surprising that there is an effect on the Second Roll Rate Peak and not the First. This can be explained somewhat by the fact that there is a larger mass (due to the Ballast) leaning in one direction at a relatively high lateral acceleration that has to be forced to roll in the opposite direction during the Second Roll Rate Peak, while during the First Roll Rate Peak the larger mass has to be moved from straight ahead position which is at zero lateral acceleration prior to the initialization of the steering movement. The First Peak Yaw Rate values are similar for the Unballasted and Ballasted outriggers. The Second Yaw Rate Peak values can occur late in the event and therefore are not included in this analysis.

Vehicle response traces from the 37.7 mph nominal speed tests are given in Figures 8.3 through 8.5. The vehicle speed and handwheel angle traces are given in Figure 8.3. The initial vehicle speeds are very similar for all four tests. The Ballasted outrigger speed traces do not drop off as rapidly late in the maneuver as the Unballasted outrigger speed traces. This may be due to the timing of the steering reversal or the lower amount steer for the Ballasted tests. The Ballasted outrigger steering reversal timing is a little later than those for the Unballasted outrigger tests. The steering reversal timing for Ballasted outrigger Test 054 is closer to those for the Unballasted tests than Test 055. The timing is not related to the ballast, but just due to driver variability.

The corrected lateral acceleration and roll angle traces are given in Figure 8.4. The corrected lateral acceleration traces are very similar for the Ballasted and Unballasted tests. Deviations appear to be as much related to steering reversal timing as much as anything else. The first part of the roll angle traces are very similar for the Ballasted and Unballasted tests. After the steering reversal, the Unballasted tests reach a higher roll angle. As noted previously though, this trend did not occur for the 44.4 mph test.

The roll rate and yaw rate traces are given in Figure 8.5. The initial roll rate peaks are very similar for all four tests. The Unballasted outrigger tests reach a higher magnitude roll rate peak during the steering reversal. The yaw rate traces for the Ballasted outriggers are slightly lower in magnitude than those for the Unballasted outriggers, but not dramatically.

Table 8.4 -- First and Second Peak Vehicle Response Data for Matched Fishhook Tests - Ballasted and Unballasted Outrigger Comparison

Vehicle	Ballast	Test No.	Initial Speed (mph)	Peak Handwheel Angle (deg)		Peak Lateral Acceleration (g)		Peak Roll Angle (deg)		Peak Roll Rate (deg/sec)		Peak Yaw Rate (deg/sec)
				First	Second	First	Second	First	Second	First	Second	First
Bronco II	No	9	37.8	-278	523	-0.69	0.80	5.4	-8.5	17.3	-35.8	-32.9
	No	48	37.7	-279	492	-0.71	0.73	6.1	-8.7	14.6	-34.6	-32.7
	Yes	54	37.7	-280	456	-0.67	0.78	5.9	-7.3	15.7	-28.2	-29.4
	Yes	55	37.8	-281	436	-0.69	0.80	5.9	-7.6	15.6	-29.7	-29.5
Bronco II	No	34	44.2	285	-516	0.76	-0.79	-5.5	8.3	-19.2	35.2	30.3
	No	35	44.6	278	-559	0.74	-0.78	-5.6	8.8	-18.0	37.8	29.8
	Yes	70	44.6	274	-459	0.75	-0.75	-6.2	8.8	-16.4	28.8	30.1
	Yes	72	44.5	270	-427	0.74	-0.76	-6.2	9.3	-18.6	30.1	30.2
	Yes	74	44.3	272	-529	0.75	-0.72	-6.3	8.7	-20.2	30.2	30.2

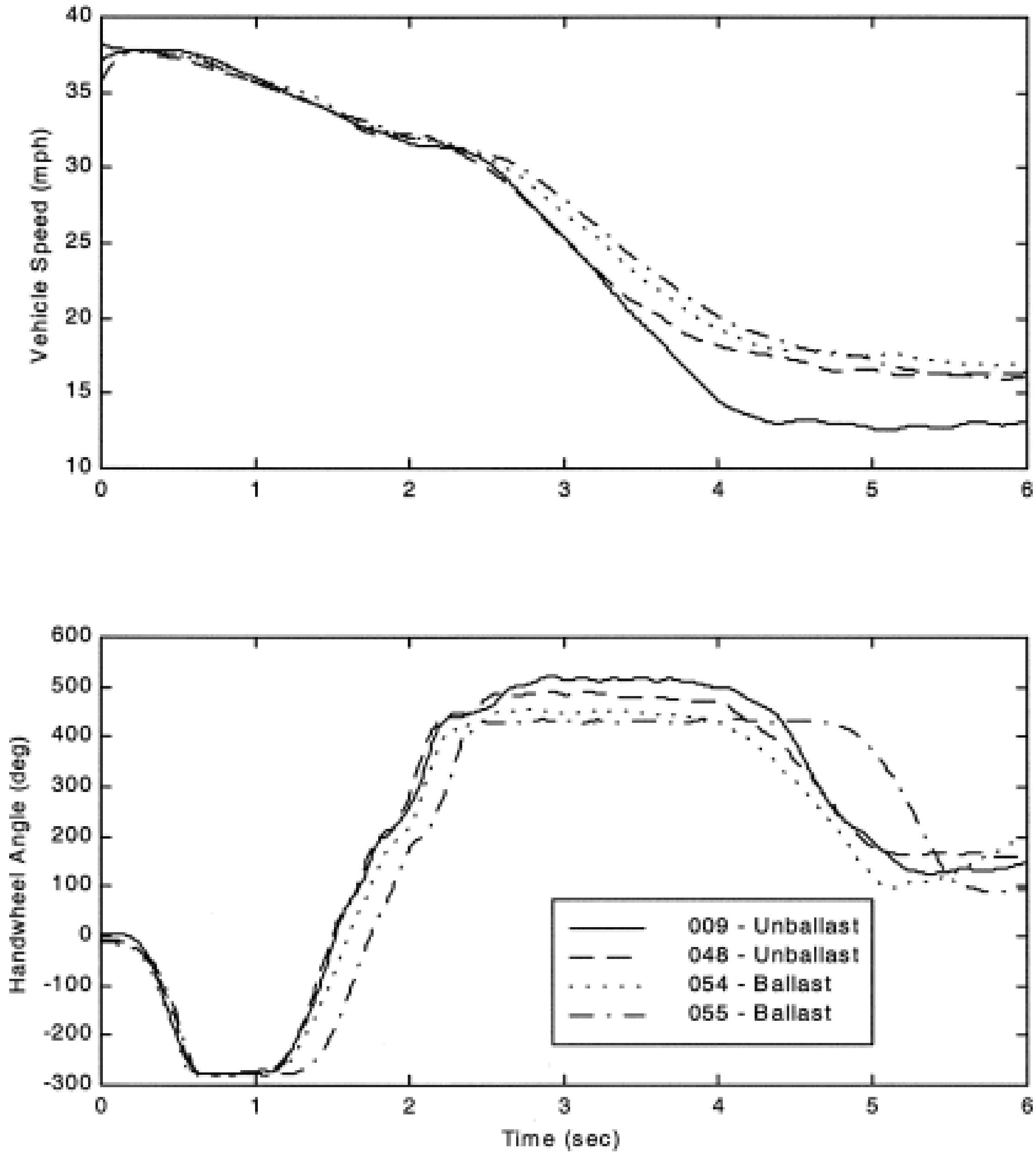
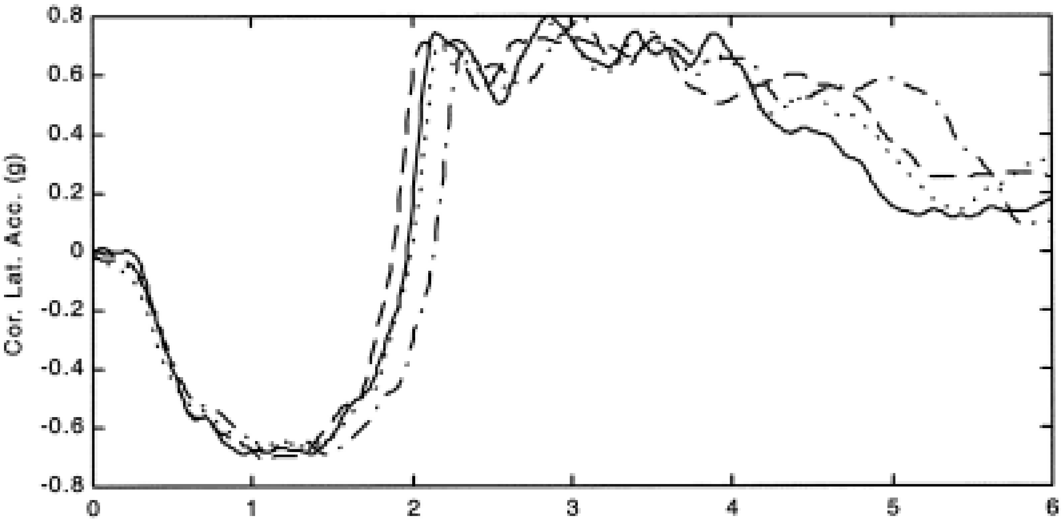


Figure 8.3 -- Vehicle Speed and Handwheel Angle for Bronco II Matched Tests 37.7 mph - Unballasted and Ballasted Outriggers



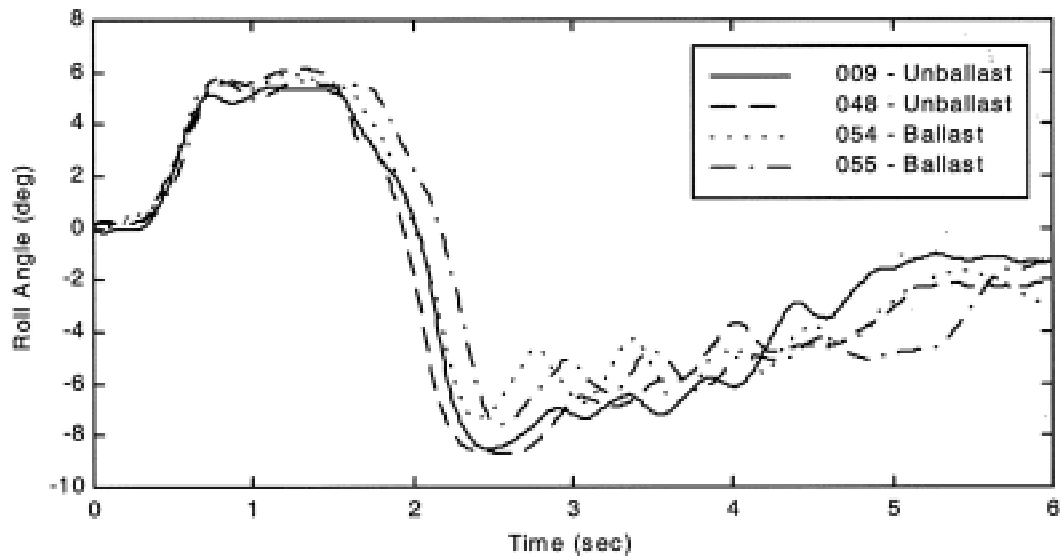
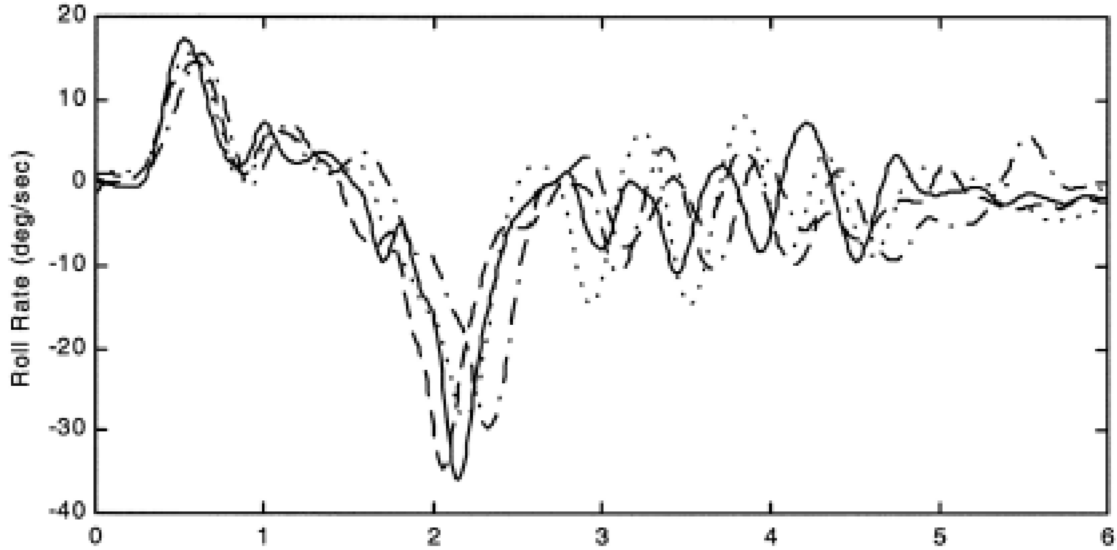


Figure 8.4 -- Corrected Lateral Acceleration and Roll Angle for Bronco II Matched Tests 37.7 mph - Unballasted and Ballasted Outriggers



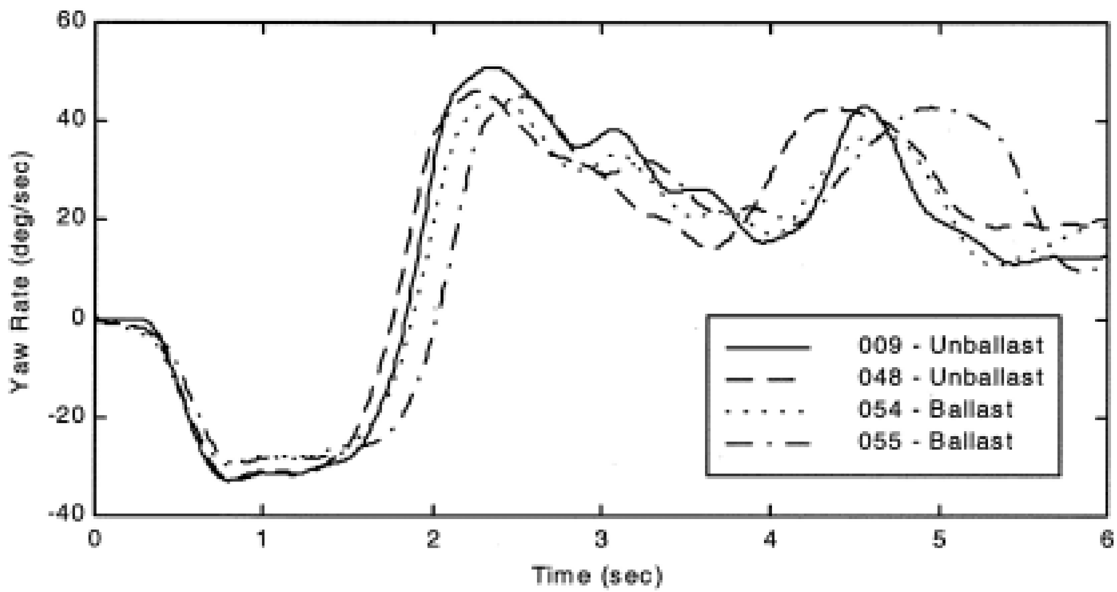


Figure 8. 5-- Roll Rate and Yaw Rate for Bronco II Matched Tests 37.7 mph - Unballasted and Ballasted Outriggers

Vehicle response traces from the 44.4 mph nominal speed tests are given in Figures 8.6 through 8.8. Only two of three Ballasted outrigger tests are shown. The vehicle speed and handwheel angle traces are given in Figure 8.6. The initial speeds are very similar for all four tests. The Ballasted outrigger speed traces do not drop off as rapidly late in the maneuver as the Unballasted outrigger speed traces. This may be due to the lower amount of steer for the Ballasted tests.

The corrected lateral acceleration and roll angle traces are given in Figure 8.7. The corrected lateral acceleration traces are very similar for the Ballasted and Unballasted tests. Deviations appear to be as much related to steering reversal timing as much as anything else. The first part of the roll angle traces are very similar for the Ballasted and Unballasted tests. After the steering reversal, the Unballasted and Ballasted peaks roll angles are similar, but the Ballasted outriggers maintain a much higher level of roll angle after the initial peak. This is probably primarily due to the extra mass of the ballast since the lateral accelerations for both outrigger conditions are very similar. The larger roll angle during the "steady state" portion after the steering reversal was not as noticeable in the 37.7 mph test, but does appear to exist.

The roll rate and yaw rate traces are given in Figure 8.8. The initial roll rate peaks are very similar for all four tests. The Unballasted outrigger tests reach a higher magnitude roll rate peak during the steering reversal. The yaw rate traces for the Ballasted outriggers are very similar up to the point of over-ranging (approximately -50 deg/sec). It cannot be determined if the vehicle had similar yaw rates or not for the two outrigger conditions during this period of over-ranging.

Both the 37.7 and 44.4 mph traces demonstrate that the driver inputs are fairly repeatable, but that a steering controller would provide much more repeatable steering inputs. This would allow for a better determination of the effect of the outriggers on test results.

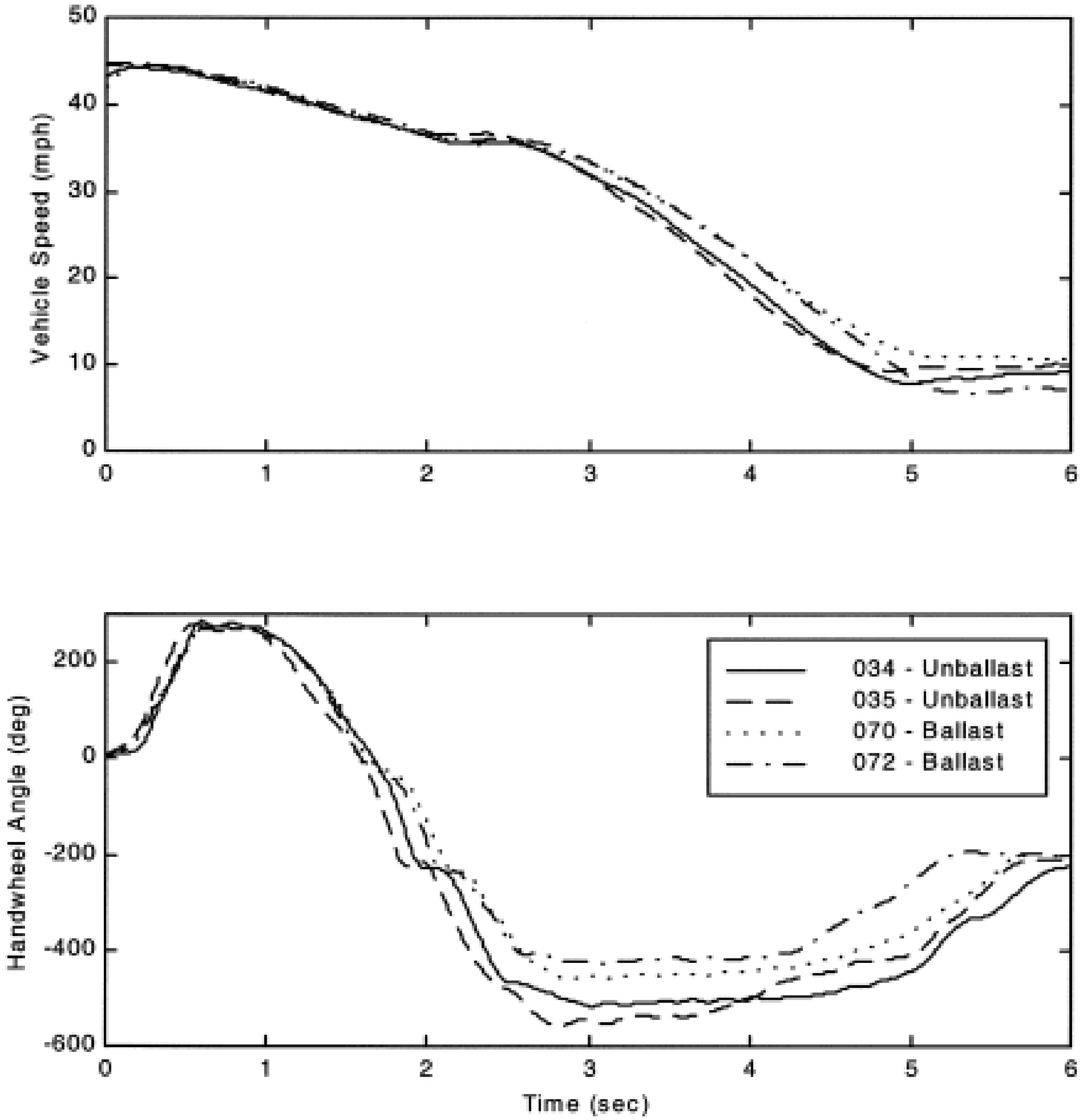


Figure 8.6 -- Vehicle Speed and Handwheel Angle for Bronco II Matched Tests 44.4 mph - Unballasted and Ballasted Outriggers

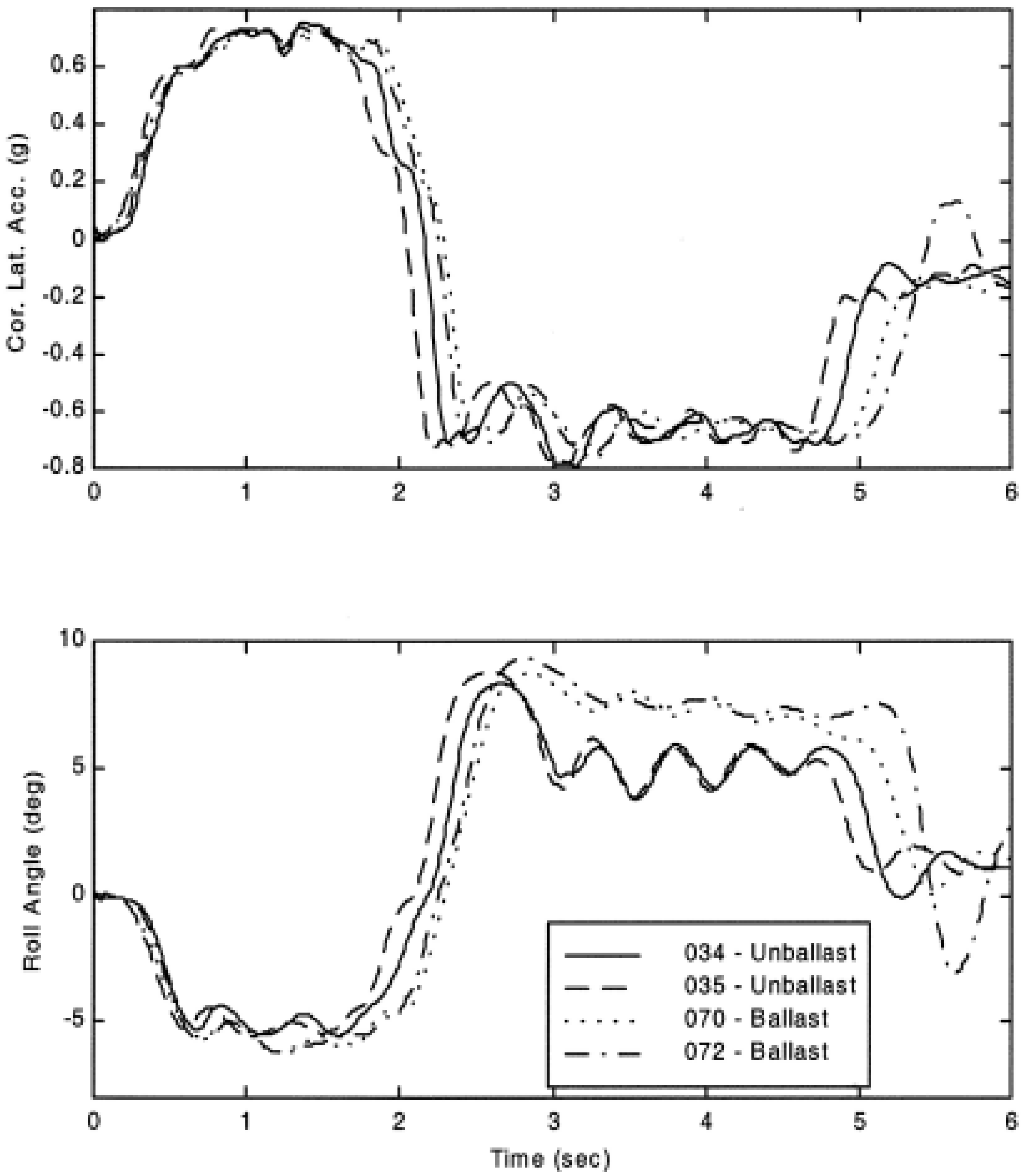


Figure 8.7 -- Corrected Lateral Acceleration and Roll Angle for Bronco II Matched Tests 44.4 mph - Unballasted and Ballasted Outriggers

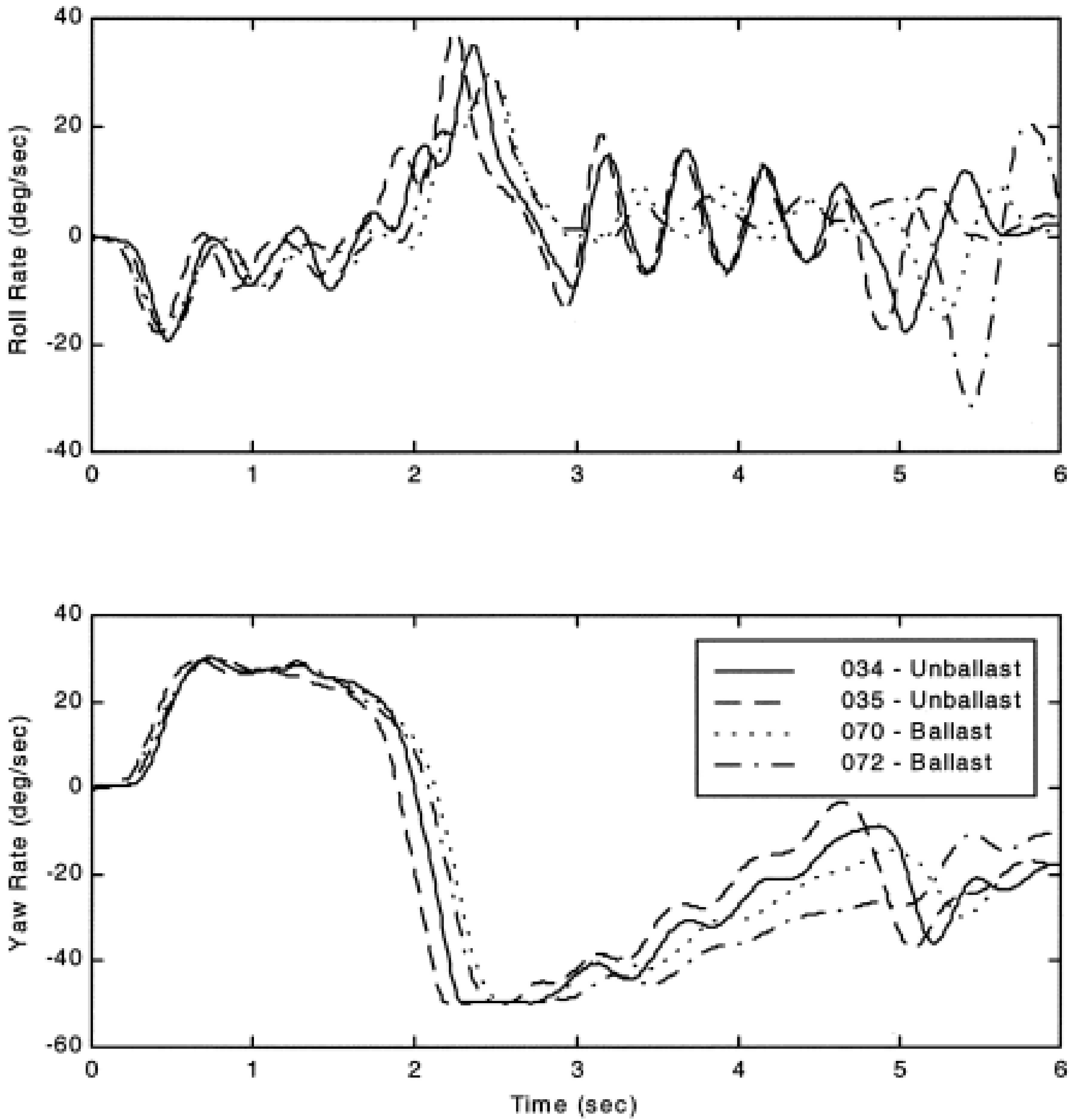


Figure 8.8 -- Roll Rate and Yaw Rate for Bronco II Matched Tests
44.4 mph - Unballasted and Ballasted Outriggers

8.2 Fishhook with Pulse Braking Maneuver and Outrigger Effects

The effect of ballast on Fishhook with Pulse Braking results was studied in a similar fashion as that for the Fishhook (without Pulse Braking). Driver A conducted one set of tests with the ballasted outriggers using the Ford Bronco II.

The Ballasted outrigger LAR values are given in Table 8.5. The Unballasted values are also listed. The Left-Right Ballasted outrigger LAR value (0.89 g) is 0.03 g higher than range of values for the corresponding Unballasted tests (0.78 to 0.86 g). The Right-Left Ballasted outrigger LAR value (-0.79 g) falls within the range for the Unballasted outrigger tests (-0.76 to -0.86 g). There was a 0.1 g difference between the Left-Right and Right-Left Ballasted outrigger LAR results.

Table 8.5 -- Fishhook with Pulse Brake LAR Values - Outrigger ComparisonTable 6.20:

Driver	Left-Right				Right-Left			
	Unballasted		Ballasted		Unballasted		Ballasted	
	Tests	LAR (g)	Tests	LAR (g)	Tests	LAR (g)	Tests	LAR (g)
A	141-145	0.86	129-138	0.89	146-152	-0.86	120-128	-0.79
	222-228	0.78			230-237	-0.76		
	248-255	0.83			240-247	-0.79		

The Minimum Initial Speed Required to Produce Two-Wheel Lift values are listed in Table 8.6. Ballasted and Unballasted results are given for comparison purposes. The Left-Right Minimum Initial Speed for the Ballasted tests is only 0.4 mph higher than the range of values for the Unballasted tests. The Right-Left value for the Ballasted tests is 1.3 mph higher than the range of values for the Unballasted tests.

Table 8.6 -- Fishhook with Pulse Brake Minimum Initial Speed Required to Produce Two-Wheel Lift - Outrigger Comparison

Driver	Minimum Initial Speed							
	Left-Right				Right-Left			
	Unballasted		Ballasted		Unballasted		Ballasted	
	Tests	Speed (mph)	Tests	Speed (mph)	Tests	Speed (mph)	Tests	Speed (mph)
A	141-145	38.2	129-138	38.6	146-152	39.0	120-128	40.3
	222-228	36.7			230-237	37.8		
	248-255	37.7			240-247	37.3		

Finding matched Ballasted and Unballasted outrigger tests for the Fishhook with Pulse Brake was not possible. The addition of a pulse brake to the maneuver adds several variables that proved very difficult to match from the data that was collected. These included pulse brake magnitude, pulse braking timing relative to the steering reversal, and pulse brake duration. To properly evaluate the effect of outriggers on individual tests with the Fishhook with Pulse Brake maneuver would require the use of a steering and braking controller that could provide repeatable steering and braking inputs.

8.3 An Examination of Outrigger Effects Using Sinusoidal Sweep Steering Inputs

Sinusoidal Sweep tests were performed using driver controlled steering inputs with the 1990 Toyota 4Runner to help determine and understand the effect of outriggers on vehicle response using frequency domain techniques. Tests were performed with no outriggers, normal outriggers, and ballasted outriggers. All testing was conducted at 36 mph. The frequency response functions between handwheel input and the following variables for the normal outrigger configuration are plotted respectively in Figures 8.9 through 8.12: corrected lateral acceleration, roll angle, roll rate, and yaw rate. The magnitude, phase and coherence functions are given in each figure. The mean and 95% confidence intervals for the mean are plotted for the magnitude and phase. The coherence tends to drop off between 0.2 and 0.3 Hz on the low end and at 1.5 Hz on the high end.

The magnitude portions for the normal outriggers for the 0.1 to 1.5 Hz frequency range are plotted in Figures 8.13 through 8.16 for each variable. The confidence intervals are fairly wide below 0.3 Hz due to the lower coherence in this range.

The magnitude portion of the frequency response functions for each outrigger condition are plotted in Figures 8.17 to 8.20 for each of the variables discussed previously. The corrected lateral acceleration plot shows that the no outrigger case has slightly greater response at higher frequencies (>0.6 Hz) than the two outrigger cases. This means the heavier the outrigger, the less the response. The opposite is true at the lower frequencies (<0.4 Hz); the lighter the outrigger, the less the response. This is generally true for the other variables, although the cross over points are at different frequencies. Of the four variables presented, only the roll rate response has a strong resonance peak. The other variables are over damped. The roll rate resonance peak is approximately 1.1 Hz for the no outrigger case. The normal outrigger has relatively flat peak over the range of 0.85 to 1.05 Hz and the ballasted outrigger has a peak at 1.0 Hz. The general decrease in natural frequency is not very large.

In general, the differences in frequency response data for the three outrigger conditions are not much greater than the bounds of the 95% confidence interval for the calculated mean value. Given this, it would be difficult to make definitive statements about the effect of the outriggers, but it does appear that for the 4Runner, the outriggers tend to dampen the response at higher frequencies and increase the response at lower frequencies. These changes appear to be relatively small especially for the normal outrigger case. The ballasted outriggers tend to increase the response at lower frequencies much more than the normal outriggers. The outriggers tended to decrease the roll rate natural frequency with increasing mass.

Fishhook 1 (see chapter 11) testing will usually be performed with a dominant frequency of 0.5 Hz. The 4Runner had very small differences in response near this frequency for the different outrigger conditions. It is expected that the outrigger effects would be more noticeable on a smaller vehicle.

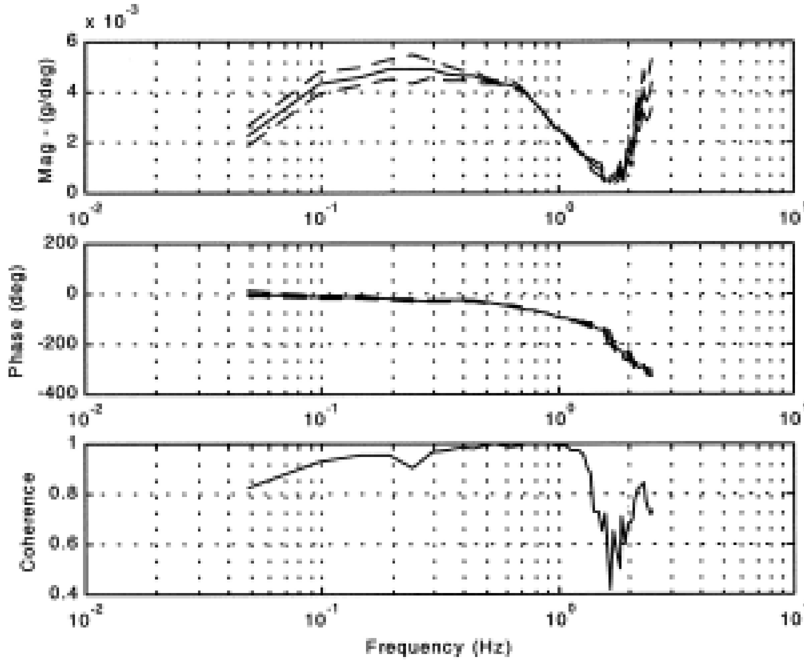


Figure 8.9 -- Corrected Lateral Acceleration Frequency Response - Normal Outriggers

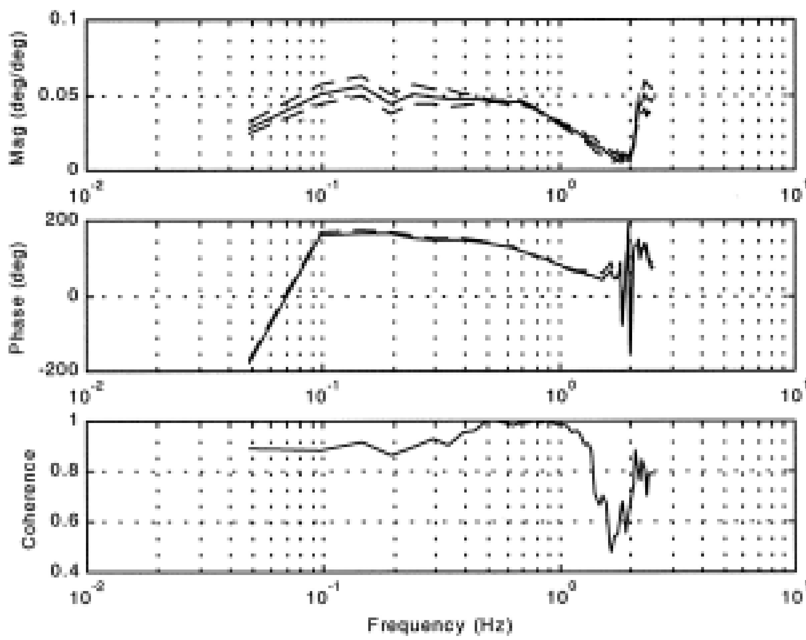


Figure 8.10-- Roll Angle Frequency Response - Normal Outriggers

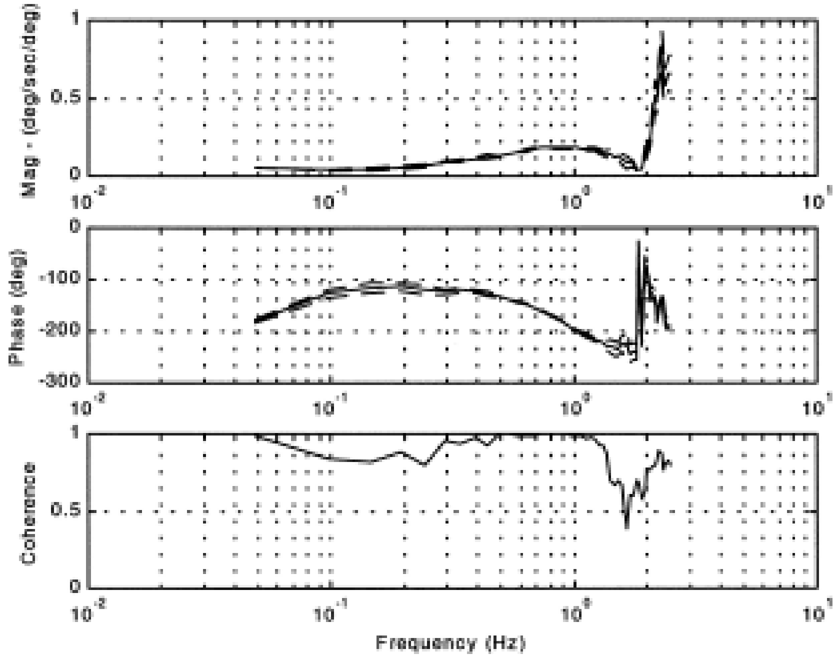


Figure 8.11 -- Roll Rate Frequency Response - Normal Outriggers

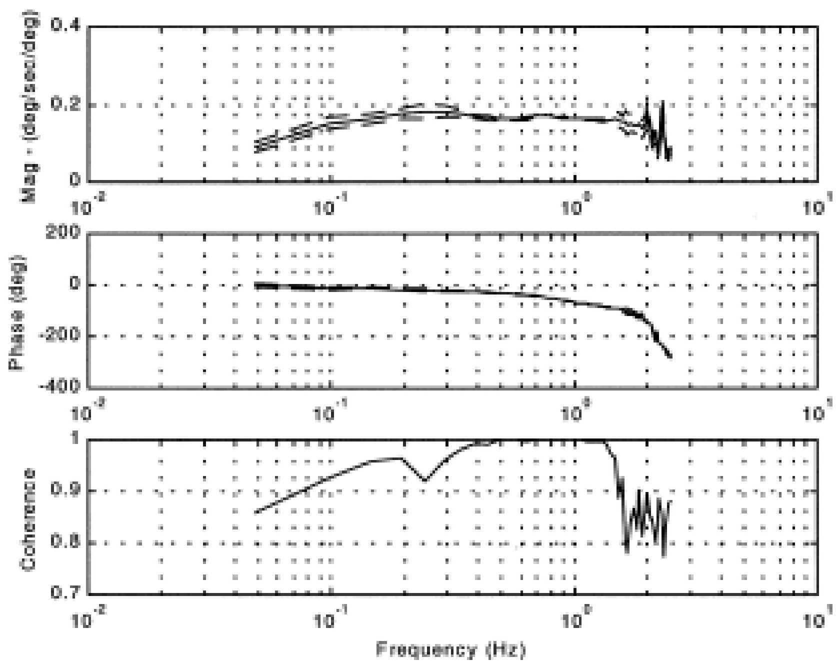


Figure 8.12 -- Yaw Rate Frequency Response - Normal Outriggers

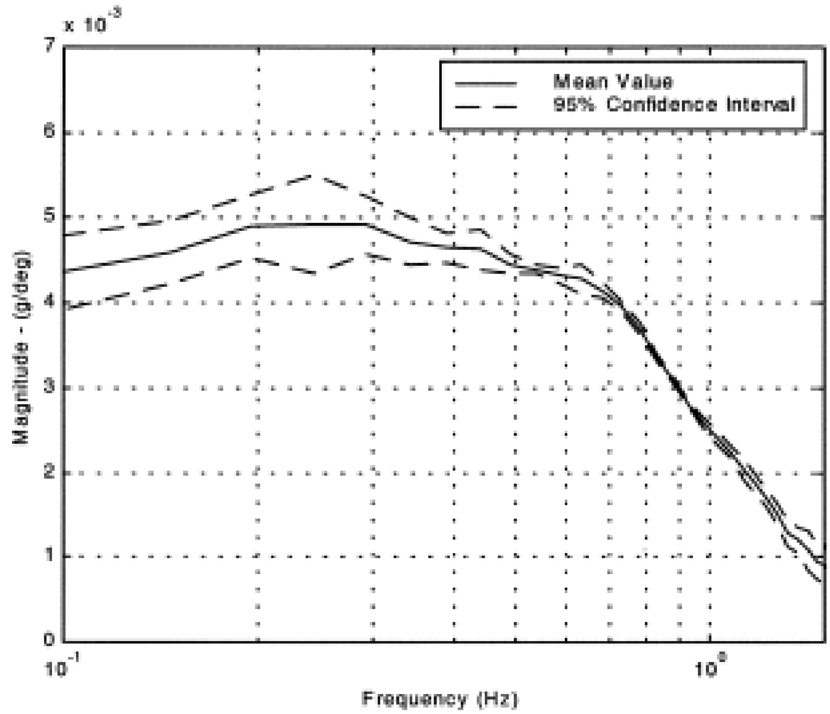


Figure 8.13 -- Corrected Lateral Acceleration Magnitude Portion of Frequency Response - Normal Outriggers

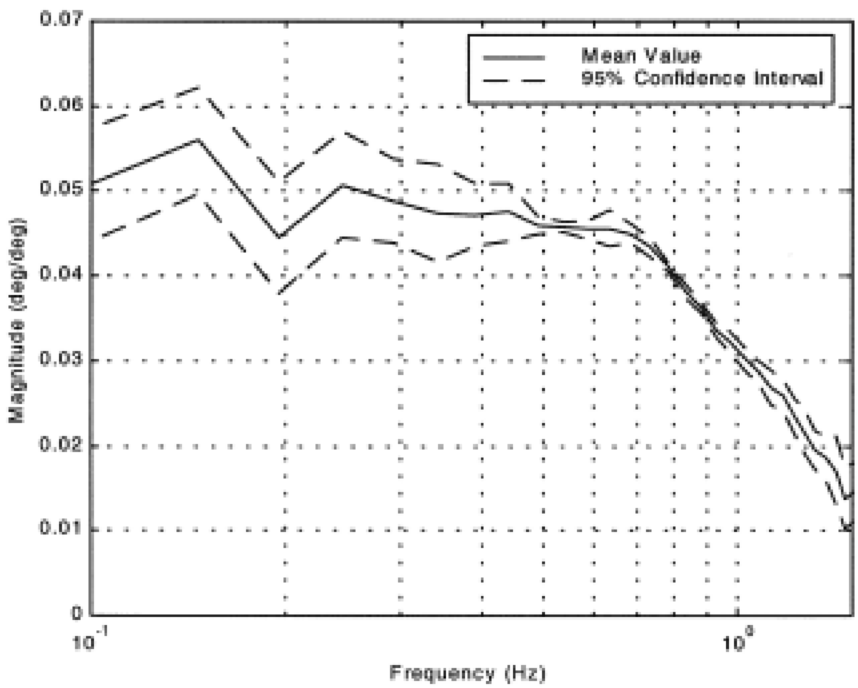


Figure 8.14 -- Roll Angle Magnitude Portion of Frequency Response - Normal Outriggers

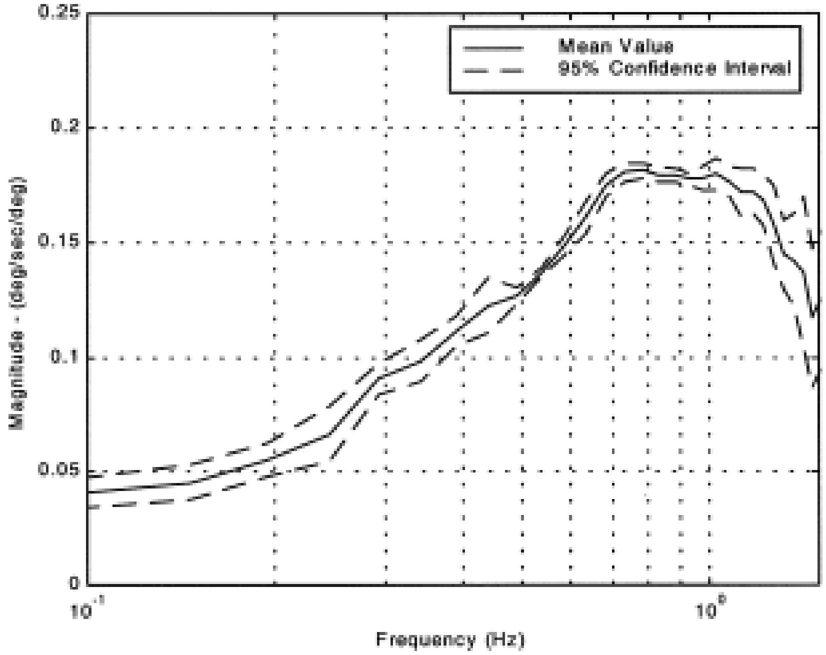


Figure 8.15 -- Roll Rate Magnitude Portion of Frequency Response - Normal Outriggers

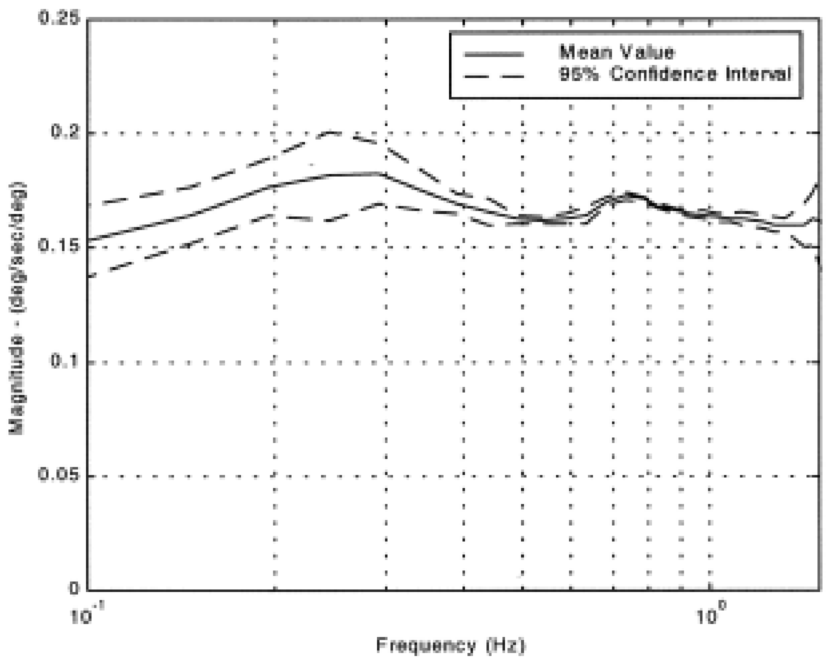


Figure 8.16 -- Yaw Rate Magnitude Portion of Frequency Response - Normal Outriggers

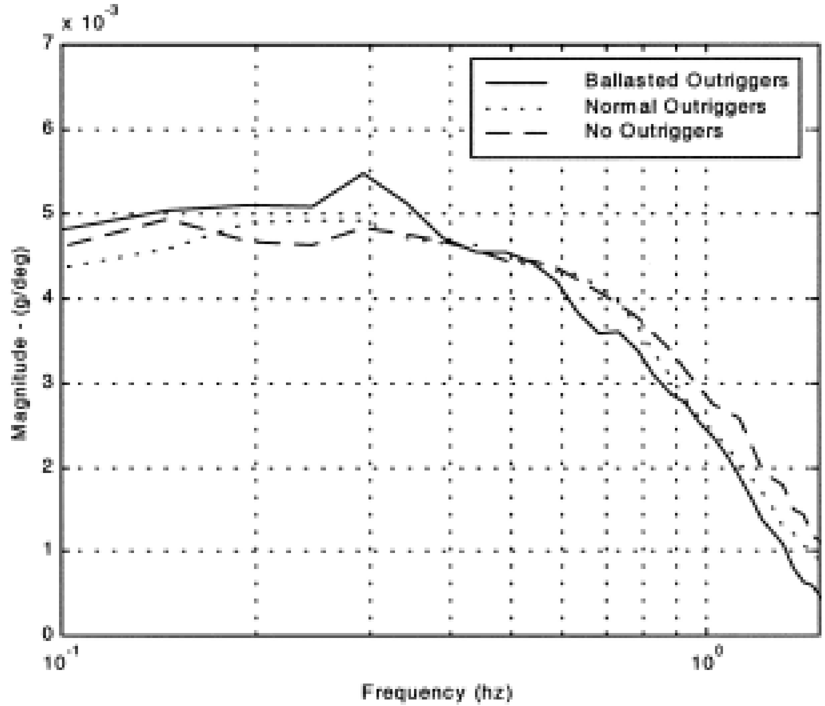


Figure 8.17 -- Corrected Lateral Acceleration Frequency Response - Outrigger Comparison

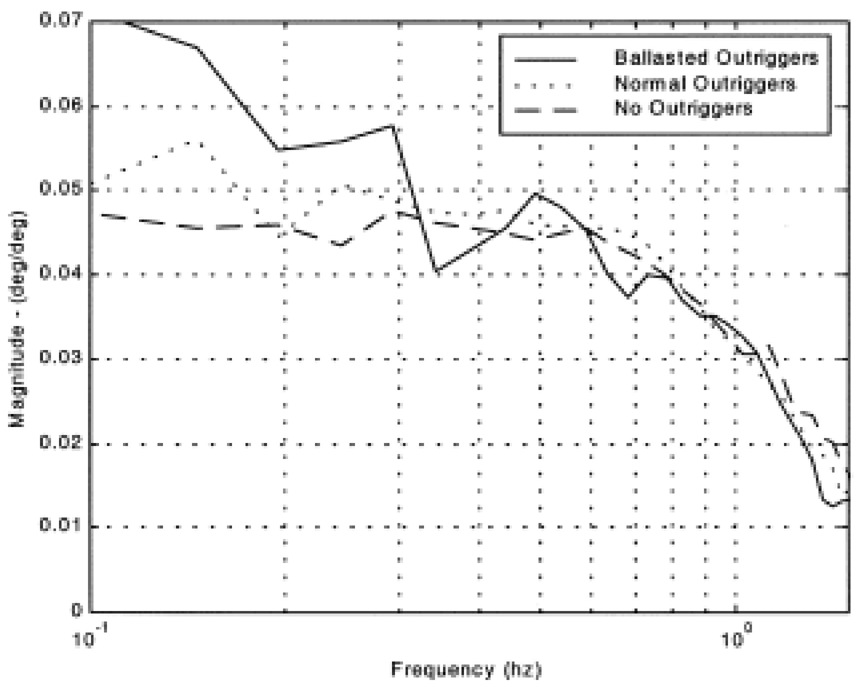


Figure 8.18 -- Roll Angle Frequency Response - Outrigger Comparison

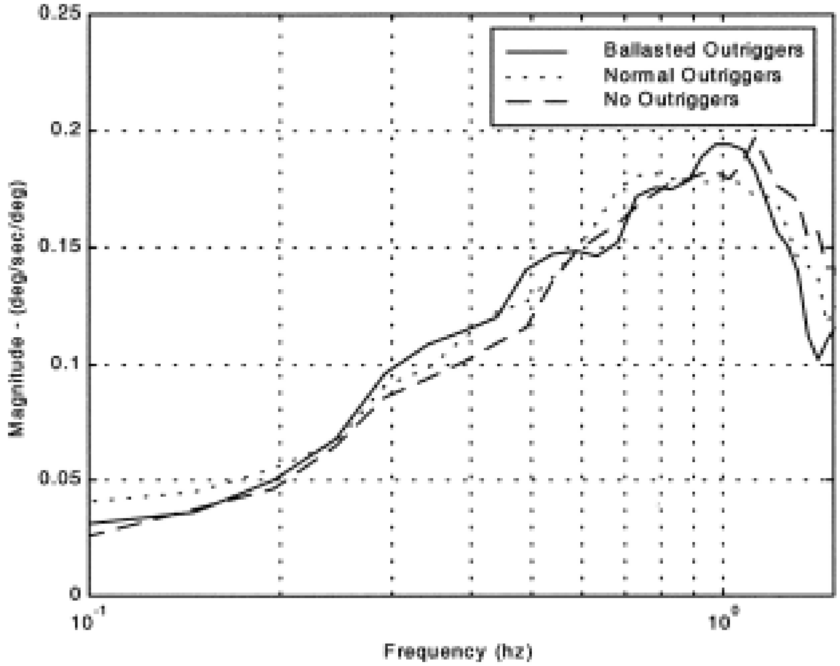


Figure 8.19 -- Roll Rate Frequency Response - Outrigger Comparison

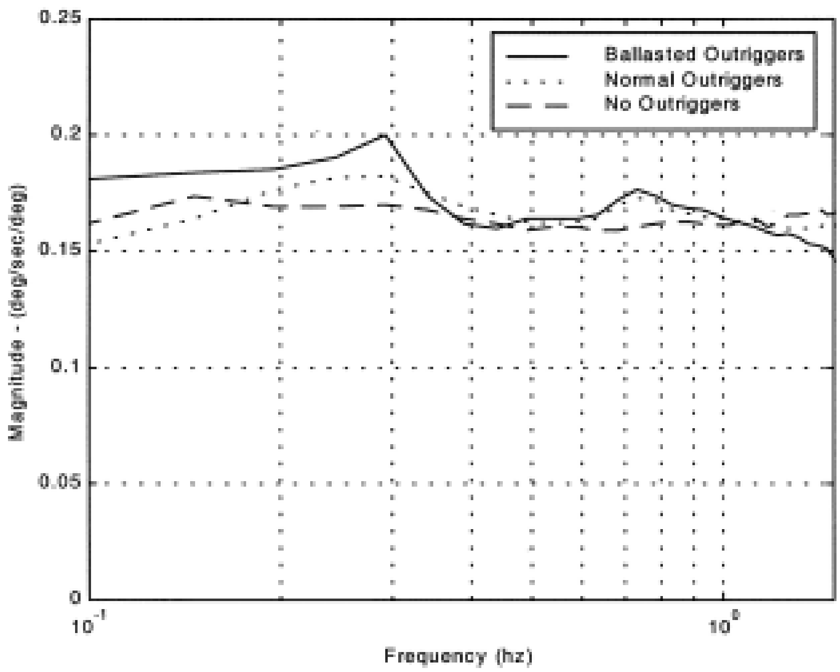


Figure 8.20 -- Yaw Rate Frequency Response - Outrigger Comparison

8.4 Summary of Outrigger Effects on Test Results

Outrigger effects were studied using three different maneuvers: the Fishhook Without Pulse Braking, the Fishhook With Pulse Braking, and Sinusoidal Sweep. Up to three outrigger conditions were evaluated with each maneuver: ballasted outriggers, normal outriggers (unballasted), and/or no outriggers. Ballasted outriggers were created by placing sandbag weights on the normal outriggers. A total of 100 lbs was added to each outrigger. This allowed the simulation of a heavier outrigger compared to the normal outriggers used in this research.

For the Fishhook Without Pulse Braking tests, Driver C performed tests with ballasted outriggers on the Toyota 4Runner, while Driver A performed tests with ballasted outriggers on the Bronco II. More test sequences would have to be performed to make a more definitive statement, but the ballast added to the outriggers did not appear to have a strong effect on the calculated LAR values, producing only slightly lower LAR values for the limited number of tests sequences conducted.

Most of the Minimum Initial Speed values for the Ballasted tests fall within the range of those for the Unballasted tests. The only exception to this was the Right-Left Driver A/Bronco II Ballasted outrigger value (44.6 mph) which was mph above the range of values for the corresponding Unballasted outrigger values (40.2 to 43.6 mph).

A comparison of individual Ballasted and Unballasted tests was made using two sets of matched tests. The first set has a nominal speed of 37.7 mph and the second 44.4 mph. The First Peak Handwheel Angles are very similar because they were controlled with a steering stop. The Second Peaks are somewhat variable, but are at a high enough angle that the tire lateral acceleration capability is believed to be saturated.

There appeared to be two main differences in the vehicle responses for the two outrigger conditions. The Ballasted outriggers produced larger peak roll rates during the steering reversal than the Unballasted outriggers. The Ballasted outriggers also maintained a much larger roll angle during the “steady state” portion after the steering reversal than the Unballasted outriggers. The Ballasted outriggers did not appear to have a strong effect on the lateral acceleration or yaw rate vehicle responses.

An examination of individual tests shows that using a steering controller to provide more repeatable steering inputs would allow a better determination of the effect of outriggers on test results.

The effect of ballast on Fishhook with Pulse Braking results was studied in a similar fashion as that for the Fishhook (without Pulse Braking). Driver A conducted one set of tests with the ballasted outriggers using the Ford Bronco II. The Left-Right Ballasted outrigger LAR value was 0.03 g higher than range of values for the corresponding Unballasted tests. The Right-Left Ballasted outrigger LAR value falls within the range for the Unballasted outrigger tests. There was a 0.1 g difference between the Left-Right and Right-Left Ballasted outrigger LAR results. The high and low values in range of LAR values for the Unballasted outrigger tests has a 0.1 g difference also. The Left-Right Minimum Initial Speed for the Ballasted tests is 0.4 mph higher than the range of values for the Unballasted tests. The Right-Left value for the Ballasted tests is 1.3 mph higher than the range of values for the Unballasted tests.

Finding matched Ballasted and Unballasted outrigger tests for the Fishhook with Pulse Brake was not possible. The addition of a pulse brake to the maneuver adds several variables that proved very difficult to match from the data that was collected. To properly evaluate the effect of outriggers on individual tests with the Fishhook with Pulse Brake maneuver would require the use of a steering and braking controller that could provide repeatable steering and braking inputs.

Sinusoidal Sweep tests were performed using driver controlled steering inputs with the 1990 Toyota 4Runner to help determine and understand the effect of outriggers on vehicle response using frequency domain techniques. Tests were performed with no outriggers, normal outriggers, and ballasted outriggers. All testing was conducted at 36 mph. The frequency response functions between handwheel input and the following variables for the normal outrigger configuration were calculated: corrected lateral acceleration, roll angle, roll rate, and yaw rate.

In general, the differences in frequency response data for the three outrigger conditions were not much greater than the bounds of the 95% confidence interval for the calculated mean value. Given this, it would be difficult to make definitive statements about the effect of the outriggers, but it does appear that for the 4Runner, the outriggers tend to dampen the response at higher frequencies and increase the response at lower frequencies. These changes appear to be relatively small especially for the normal outrigger case. The ballasted outriggers tend to increase the response at lower frequencies much more than the normal outriggers. It is expected that the outrigger effects would be more noticeable on a smaller vehicle.

9.0 FUEL LEVEL EFFECTS ON TEST RESULTS

The effect of fuel level on test results was evaluated by performing tests with a low fuel level and a full fuel level. The Fishhook Without Pulse Braking maneuver was the only one used to evaluate the effects of fuel level. Testing was primarily conducted with a low fuel level with a limited number of test sets being conducted with a full fuel level. Data from the low fuel level testing were shown earlier in Chapter 7.

9.1 Fuel Level Effect Testing Performed

Drivers A and C conducted one set of Fishhook Without Pulse Braking tests each with the higher fuel level. For each testing set, tests were conducted with both a Right-Left steering input and a Left-Right steering input.

The peak vehicle responses for all of the driver controlled Fishhook tests are given in Appendix A. As was the case for the Fishhook results presented in Chapter 7, the primary focus of this chapter will be on Minimum Initial Speed Required to Produce Two-Wheel Lift and Lateral Acceleration at Rollover (LAR) values for the various combinations of tests conducted.

9.2 The Effects of Fuel Level on Fishhook Test Results

The effect of fuel level on test results was evaluated by performing tests with a low fuel level and a full fuel level using the 1990 Toyota 4Runner. Both Drivers A and C conducted one set of tests with the full fuel level and two sets with the lower fuel level. The LAR results for both the lower and full fuel level testing are given in Tables 9.1 and 9.2 for First and Second Peak respectively.

For the limited number of test sequences performed, neither the First nor Second Peak LAR values are affected by a low versus full fuel level. The largest difference occurs for the Second Peak value for Driver A in the Right-Left steer combination (Tests 241-245), but this difference is probably artificially high (0.05 g) due to the LAR value listed for Full Tank being artificially low (0.69 g) since all the tests had two-wheel lift on the Second Peak for this test sequence. The average values for both First Peak and Second Peak LAR's are very similar for the two fuel loading conditions.

The Minimum Initial Speed Required to Produce Two-Wheel Lift values are given in Table 9.3. For the limited number of test sequences performed, the Minimum Initial Speed values do not appear to be affected by a low versus full fuel level. The average values for each steer combination are very similar for the two fuel loading conditions tested.

Table 9.1 -- LAR Values Using First Peak - Fuel Loading Level Comparison for Toyota 4Runner with Larger Tires

Driver	Left-Right				Right-Left			
	Low Fuel		Full Tank		Low Fuel		Full Tank	
	Tests	LAR (g)	Tests	LAR (g)	Tests	LAR (g)	Tests	LAR (g)
A	040-042	N.A.	234-240	0.63	030-038	-0.67	241-245	-0.63*
	045-053	0.64			055-061	-0.66		
C	084-094	0.66	223-231	0.65**	095-102	-0.64	216-222	-0.64
	110-115	0.62			105-109	-0.66		
Average		0.64		0.63		-0.66		-0.64

* - All tests had two-wheel lift - min value listed - not used in average

** - No tests had two-wheel lift on first roll peak - max value listed - not used in average

Table 9.2 -- LAR Values Using Second Peak - Fuel Loading Level Comparison for Toyota 4Runner with Larger Tires

Driver	Left-Right				Right-Left			
	Low Fuel		Full Tank		Low Fuel		Full Tank	
	Tests	LAR (g)	Tests	LAR (g)	Tests	LAR (g)	Tests	LAR (g)
A	040-042	N.A.	234-240	0.74	030-038	-0.74	241-245	-0.69*
	045-053	0.76			055-061	-0.80**		
C	084-094	0.71	223-231	0.73	095-102	-0.74	216-222	-0.73
	110-115	0.72			105-109	-0.76**		
Average		0.73		0.73		-0.74		-0.73

* - All tests had two-wheel lift - min value listed - not used in average

** - No tests had two-wheel lift on second roll peak - max value listed - not used in average

Table 9.3 -- Minimum Initial Speed Required to Produce Two-Wheel Lift - Fuel Loading Level Comparison for Toyota 4Runner with Larger Tires

Driver	Left-Right				Right-Left			
	Low Fuel		Full Tank		Low Fuel		Full Tank	
	Tests	Speed (mph)	Tests	Speed (mph)	Tests	Speed (mph)	Tests	Speed (mph)
A	040-042	N.A.	234-240	35.2	030-038	35.1	241-245	33.7*
	045-053	36.7			055-061	34.5		
C	084-094	37.8	223-231	37.9**	095-102	32.5	216-222	34.5
	110-115	36.2			105-109	35.0		
	Average	36.9		35.2		34.3		34.5

* - All tests had two-wheel lift - min value listed - not used in average

** - No tests had two-wheel lift on first peak, lowest speed with two-wheel lift on second peak is listed - not used in average

It should be noted that a half-full fuel tank may create a worse condition than the full fuel and low fuel conditions tested. The gas in a half-full fuel tank may have more of a tendency to slosh which could adversely affect vehicle performance. It should also be noted that the tank on the 4Runner was located on the right-side of the vehicle and has a long narrow shape. If the fuel tank was at the rear of the vehicle and had a wider shape, the effect of the gas sloshing in the tank could be more adverse.

To analyze the effects of fuel level on test results, it would be best to have highly repeatable steering and throttle inputs. Because this testing was performed using driver generated steering inputs, it is hard to examine the effects of fuel level without the driver influencing test results. The individual test runs were examined though to find tests that had similar vehicle speed and handwheel angle traces. The results from two of these tests are plotted in Figures 9.1 and 9.2. Test 93 had a low fuel level and Test 231 had a full fuel level. Both tests were performed by Driver C.

From the results presented in Figure 9.1, the vehicle speed traces are very similar up to approximately 3.5 seconds. The steering reversal has been completed at this point and the handwheel angle is still being held at its maximum input. The initial steering input to -270 degrees is very similar for the two tests. The steering reversal is very similar up to the point of +200 degrees. There is some deviation between the two traces as the steering reversal is completed, but they are still fairly similar.

The corrected lateral acceleration and roll angle traces for Tests 93 and 231 are plotted in Figure 9.2. The traces for these two tests are very similar. The amount of variability seen in these results does not appear to be any greater than tests with same fuel level that have a similar degree of variability in driver controlled inputs (vehicle speed/throttle and handwheel angle).

9.3 Summary of Fuel Level Test Results.

Two drivers performed both low fuel and full fuel level tests with the 1990 Toyota 4Runner. Fuel level did not appear to have a strong influence on test results. The LAR and Minimum Initial Speed Required to Produce Two-Wheel Lift values were very similar for the two fuel level conditions. An examination of two individual test runs with similar vehicle speed and steering inputs showed that fuel level did not appear to have any strong influence on test results. It should be noted that a half-full fuel tank may create a worse condition than the full fuel and low fuel conditions tested. The gas in a half-full fuel tank may have a tendency to slosh which could adversely affect vehicle performance. Since there appears to be no major difference in response, all testing in Phase II will be done with a full fuel level for testing convenience.

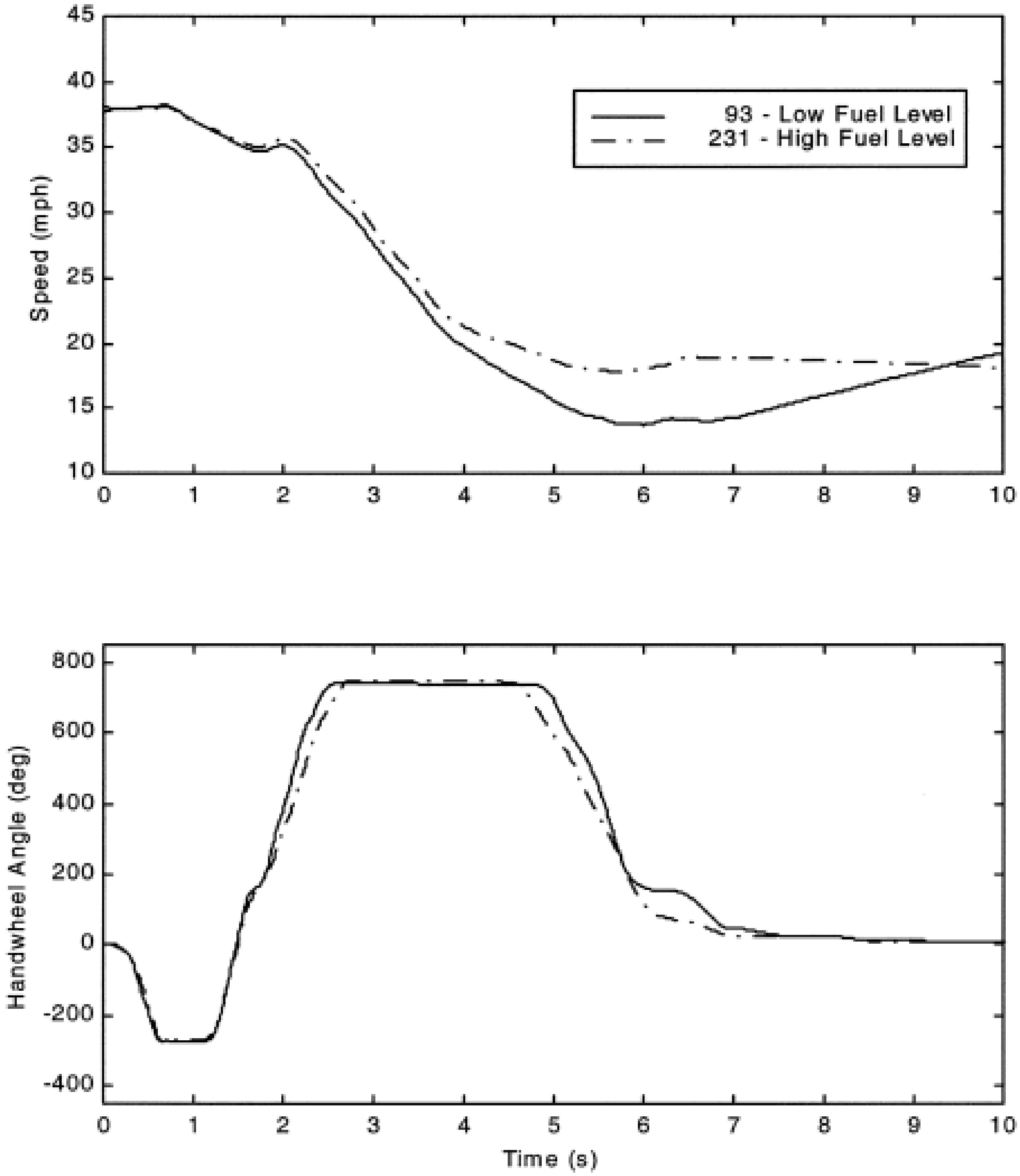


Figure 9.1 -- Vehicle Speed and Handwheel Angle Traces for 4Runner Low and Full Fuel Level Matched Tests 93 and 231

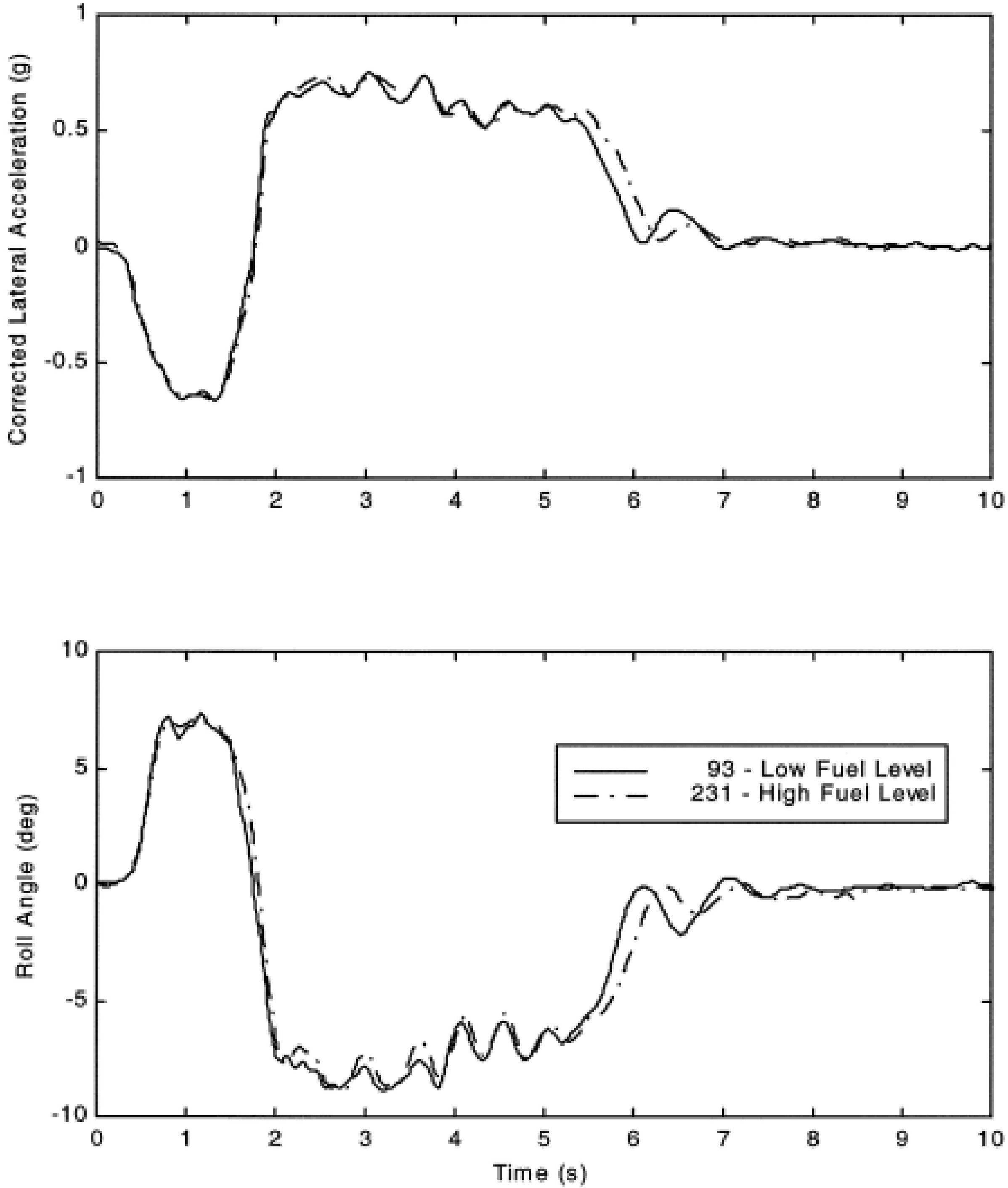


Figure 9.2 -- Corrected Lateral Acceleration and Roll Angle Traces for 4Runner Low and Full Fuel Level Matched Tests 93 and 231

10.0 STEERING CONTROLLER TEST RESULTS AND ANALYSIS

Steering controller tests were performed using three maneuvers: J-Turn with Pulse Braking, Fishhook without Pulse Braking, and Resonant Steer. The results from testing for each of these test procedures are given in the following sections.

10.1 J-Turn With Pulse Braking Maneuver Test Results - Analysis - Steering Controller Study

This testing had two main goals; determine how best to implement the J-Turn (With and Without Pulse Braking) maneuver in Phase II research using the controller and to examine the effect of different levels of pulse braking (magnitude of brake pedal force) on vehicle responses. All tests were performed with the 1990 Toyota 4Runner.

10.1.1 J-Turn With Pulse Braking Tests Performed for Each Vehicle

For one part of this steering controller study, two sets of tests were performed to see the effect of a lower brake pedal force versus a higher brake pedal force on J-Turn with Pulse Braking overall results, i.e., does a lower brake pedal force require a higher speed to achieve two-wheel lift.

For the second part of the steering controller study, the test speed was kept constant (approximately 40 mph) and the driver was asked to provide varying levels of brake pedal force.

Test results for both parts of this steering controller study are given in Tables 10.1 through 10.3. The results from three testing categories are listed: higher brake force with increasing speed, lower brake force with increasing speed, and variable brake force with fixed initial speed. The higher and lower brake force with increasing speed results will be discussed in Section 10.1.2 while the variable brake force results will be discussed in Section 10.1.3.

Table 10.1 lists the Test Number, Initial Speed, Handwheel Angle, Peak Handwheel Rate, Average Handwheel Rate, Pulse Brake Magnitude and Duration, Deceleration due to Turn, and Deceleration due to Turn and Brake. The Higher and Lower Brake Force with Increasing Speed results are given at the top of the table while the Variable Brake Forced with Fixed Initial Speed are given at the bottom of the table. This will be a consistent format for Tables 10.2 and 10.3.

The Peak and "Dip" Roll Angle and Corrected Lateral Acceleration values are given in Table 10.2. The Amount of Two-Wheel Lift is also listed. The Peak and "Dip" Roll Rate and Yaw Rate values are given in Table 10.3. The Test Number, Initial Speed, Handwheel Angle, and Brake Pedal Force are repeated in Tables 10.2 and 10.3.

Tests 349-353 for the Higher Brake Force had a similar speed range for all the tests conducted with the Lower Brake Force, so they were averaged to allow the two sets of data to be compared. These average results are also listed in Tables 10.1 through 10.3.

10.1.2 A Comparison of Higher Versus Lower Brake Pulse Magnitude Results

Tests 349 through 353 for the Higher Brake Force tests had a similar speed range to Tests 354 through 358 for the Lower Brake Force tests. Average values for these test ranges are presented in Tables 10.1 through 10.3.

As seen in Table 10.1, the Higher and Lower Brake Force values had an average of approximately 220 and 120 pound-force respectively. The Higher Brake Force had a longer Pulse Brake Duration on average. As would be expected, the Deceleration due to Turn (prior to the brake pulse) for the two sets of data were the same. The Deceleration due to Turn and Brake was approximately 1/3 higher for the Higher Brake Force tests (0.82 versus 0.61 g's).

Table 10.1: -- Steering Controller J-Turn with Pulse Brake Results - Handwheel Rate, Pulse Brake, and Deceleration Values

Test Condition	Test No.	Initial Speed (mph)	Hand-wheel Angle (deg)	Peak Handwheel Rate (deg/sec)	Average Handwheel Rate (deg/sec)	Pulse Brake Magnitude (lbf)	Pulse Brake Duration (sec)	Decel due to Turn (g)	Decel due to Turn & Brake (g)
Higher Brake Force with Increasing Speed	345	29.6	-328	-1169	-800	181	0.36	-0.19	-0.72
	346	33.3	-327	-1172	-821	167	0.32	-0.21	-0.70
	347	37.8	-327	-1168	-819	200	0.36	-0.23	-0/79
	348	38.5	-328	-1161	-797	204	0.34	-0.23	-0.78
	349	40.4	-327	-1174	-813	197	0.38	-0.19	-0.81
	350	43.4	-328	-1181	-815	185	0.38	-0.23	-0.79
	351	43.2	-326	-1174	-815	247	0.37	-0.22	-0.81
	352	45.8	-327	-1161	-812	243	0.35	-0.26	-0.83
	353	47.7	-327	-1162	-719	244	0.36	-0.25	-0.87
				Average	-794.8	223.2	0.37	-0.23	-0.82
Lower Brake Force with Increasing Speed	354	39.8	-324	-1125	-768	128	0.28	-0.23	-0.60
	355	41.1	-327	-1161	-812	150	0.3	-0.22	-0.66
	356	43.5	-327	-1188	-807	68	0.2	-0.23	-0.45
	357	42.9	-328	-1164	-811	144	0.38	-0.24	-0.74
	358	46.1	-327	-1164	-811	113	0.24	-0.24	-0.60
				Average	-801.8	120.6	0.28	-0.23	-0.61
Variable Brake Force with Fixed Initial Speed	360	39.7	-328	-1164	-788	34	0.17	-0.22	-0.37
	363	42.5	-327	-1151	-814	52	0.17	-0.24	-0.39
	362	42.9	-328	-1170	-807	82	0.19	-0.22	-0.41
	361	42.6	-328	-1159	-795	109	0.20	-0.23	-0.49
	365	42.6	-327	-1147	-817	131	0.28	-0.23	-0.59
	364	41.1	-328	-1173	-818	162	0.29	-0.23	-0.64
	366	41.5	-327	-1156	-792	189	0.33	-0.22	-0.80
	368	42.5	-327	-1185	-807	198	0.34	-0.22	-0.76
	367	39.7	-328	-1152	-797	263	0.37	-0.24	-0.83
	376	38.7	327	1153	696	69	0.24	-0.24	-0.52
	374	37.4	327	1155	730	105	0.22	-0.25	-0.53
	375	37.5	326	1155	696	108	0.24	-0.22	-0.54
	372	41.3	326	1156	667	114	0.23	-0.24	-0.54
	371	40.5	327	1130	696	161	0.30	-0.24	-0.68
	369	41.8	326	1122	682	180	0.34	-0.24	-0.65
	370	40.4	327	1145	741	242	0.35	-0.24	-0.76

Table 10.2 -- Steering Controller J-Turn with Pulse Brake Results - Roll Angle, Two-Wheel Lift, and Corrected Lateral Acceleration Values

Test Condition	Test No.	Initial Speed (mph)	Hand-wheel Angle (deg)	Brake Pedal Force (lbf)	Peak Roll Angle Pre-Pulse (deg)	Roll Angle Dip due to Pulse (deg)	Peak Roll Angle Post-Pulse (deg)	Amount of Two-Wheel Lift	Peak Cor. Lat. Acc. Pre-Pulse (g)	Cor. Lat. Acc. Dip due to Pulse (g)	Peak Cor. Lat. Acc. Post-Pulse (g)
Higher Brake Force with Increasing Speed	345	29.6	-328	181	6.9	4.8	6.3	None	-0.75	-0.58	-0.73
	346	33.3	-327	167	6.9	5.8	7.2	None	-0.76	-0.65	-0.79
	347	37.8	-327	200	7.1	5.5	7.9	None	-0.78	-0.64	-0.81
	348	38.5	-328	204	7.0	5.2	8.2	None	-0.80	-0.64	-0.82
	349	40.4	-327	197	7.1	4.0	8.4	None	-0.64	-0.52	-0.92
	350	43.4	-328	185	7.2	5.8	8.3	None	-0.77	-0.67	-0.89
	351	43.2	-326	247	7.1	5.3	8.8	None	-0.80	-0.63	-0.90
	352	45.8	-327	243	7.3	5.5	8.4	None	-0.84	-0.66	-0.90
	353	47.7	-327	244	7.3	5.0	10.9	Minor	-0.80	-0.62	-0.96
				Average	7.2	5.1	9.0		-0.77	-0.62	-0.91
Lower Brake Force with Increasing Speed	354	39.8	-324	128	7.2	6.7	7.7	None	-0.83	-0.75	-0.87
	355	41.1	-327	150	7.2	6.0	8.0	None	-0.83	-0.75	-0.89
	356	43.5	-327	68	7.3	6.5	8.0	None	-0.86	-0.79	-0.88
	357	42.9	-328	144	7.1	6.2	8.0	None	-0.77	-0.68	-0.87
	358	46.1	-327	113	7.4	6.3	10.7	Minor	-0.77	-0.73	-0.96
				Average	7.2	6.3	8.5		-0.81	-0.74	-0.89
Variable Brake Force with Fixed Initial Speed	360	39.7	-328	34	7.8	6.5	7.7	None	-0.84	-0.76	-0.83
	363	42.5	-327	52	7.8	7.1	7.8	None	-0.88	-0.80	-0.86
	362	42.9	-328	82	8.2	6.6	8.3	None	-0.85	-0.77	-0.88
	361	42.6	-328	109	7.4	6.3	7.6	None	-0.83	-0.75	-0.88
	365	42.6	-327	131	7.4	6.3	8.8	None	-0.84	-0.76	-0.91
	364	41.1	-328	162	7.5	6.5	8.5	None	-0.81	-0.74	-0.88
	366	41.5	-327	189	7.5	5.2	9.7	None	-0.79	-0.64	-0.92
	368	42.5	-327	198	7.5	5.8	9.7	None	-0.85	-0.67	-0.89
	367	39.7	-328	263	7.4	5.4	9.6	None	-0.83	-0.59	-0.89
	376	38.7	327	69	-7.8	-6.4	-8.4	None	0.80	0.71	0.90
	374	37.4	327	105	-8.0	-6.5	-9.3	None	0.79	0.67	0.87
	375	37.5	326	108	-7.4	-6.7	-8.8	None	0.77	0.69	0.88
	372	41.3	326	114	-8.1	-6.3	-9.3	None	0.80	0.69	0.94
	371	40.5	327	161	-7.6	-5.6	-9.5	None	0.78	0.64	0.93
	369	41.8	326	180	-7.8	-5.3	-9.1	None	0.81	0.56	0.82
	370	40.4	327	242	-7.5	-4.6	-9.5	None	0.77	0.53	0.88

Table 10.3 -- Steering Controller J-Turn with Pulse Brake Results - Roll Rate and Yaw Rate Values

Test Condition	Test No.	Initial Speed (mph)	Handwheel Angle (deg)	Brake Pedal Force (lbf)	Peak Roll Rate Pre-Pulse (deg/sec)	Roll Rate Dip due to Pulse (deg/sec)	Peak Roll Rate Post-Pulse (deg/sec)	Peak Yaw Rate Pre-Pulse (deg/sec)	Yaw Rate Dip due to Pulse (deg/sec)	Peak Yaw Rate Post-Pulse (deg/sec)
Higher Brake Force with Increasing Speed	345	29.6	-328	181	25.8	-8.0	14.4	-31	-19.5	-34.8
	346	33.3	-327	167	27	-2.7	5.6	-31.4	-21.2	-32.8
	347	37.8	-327	200	26.3	-5.0	15.2	-31.8	-18.7	-32.2
	348	38.5	-328	204	27.3	-7.2	17.3	-32.2	-18.6	-31.1
	349	40.4	-327	197	27.8	-13.5	29.0	-29.0	-20.1	-31.3
	350	43.4	-328	185	28.6	-2.2	17.6	-30.6	-20.2	-29.9
	351	43.2	-326	247	28.3	-7.0	19.2	-30.5	-17.2	-30.1
	352	45.8	-327	243	28.9	-10.2	18.2	-31.4	-20.3	-31.3
	353	47.7	-327	244	29.0	-6.6	23.5	-31.6	-20.5	-31.4
				Average	28.5	-7.9	21.5	-30.6	-19.7	-30.8
Lower Brake Force with Increasing Speed	354	39.8	-324	128	28.5	-3.0	8.1	-32.1	-24.5	-32.3
	355	41.1	-327	150	28.4	-5.5	12.1	-32.2	-24.3	-32.2
	356	43.5	-327	68	29.2	-5.8	9.1	-31.3	-25.8	-31.1
	357	42.9	-328	144	28.7	-0.9	10.3	-31.0	-23.9	-31.8
	358	46.1	-327	113	29.3	-4.1	15.8	-30.6	-27.3	-32.5
				Average	28.8	-3.9	11.1	-31.4	-25.2	-32.0
Variable Brake Force with Fixed Initial Speed	360	39.7	-328	34	30.2	-9.3	9.4	-32.6	-18.2	-31.8
	363	42.5	-327	52	29.3	-2.0	6.2	-31.6	-19.0	-31.6
	362	42.9	-328	82	30.4	-10.4	12.3	-31.9	-23.8	-32.5
	361	42.6	-328	109	29.4	-7.1	10.0	-32.3	-21.5	-30.1
	365	42.6	-327	131	29.6	-6.7	15.7	-32.6	-24.1	-32.2
	364	41.1	-328	162	30.0	-3.8	11.6	-33.0	-24.5	-32.4
	366	41.5	-327	189	30.1	-6.4	21.1	-32.4	-21.9	-31.9
	368	42.5	-327	198	30.0	-8.2	18.4	-33.0	-20.9	-32.0
	367	39.7	-328	263	29.1	-12.8	22.7	-33.5	-18.6	-32.5
	376	38.7	327	69	-28.2	7.0	-18.7	37.7	33.1	44.7
	374	37.4	327	105	-27.3	9.2	-14.8	37.2	31.6	40.4
	375	37.5	326	108	-27.8	3.9	-14.7	37.1	32.4	39.1
	372	41.3	326	114	-28.0	9.7	-20.4	36.3	29.9	42.3
	371	40.5	327	161	-27.9	10.2	-21.5	35.9	27.5	37.7
	369	41.8	326	180	-28.2	12.1	-21.7	33.8	18.2	36.5
	370	40.4	327	242	-27.9	12.5	-25.7	34.5	19.1	36.2

From the results presented in Table 10.2, the Peak Roll Angles and Peak Lateral Accelerations Pre-Pulse values are very similar for the Higher and Lower Brake Force groups. This suggests that the Pre-Pulse part of the test is repeatable. The Peak Roll Angle and Lateral Acceleration Dips due to Pulse were greater (lower magnitude = greater dip) on average for the Higher Brake Force values (5.1 verus 6.3 degrees and 0.62 versus 0.74 g). The Peak Roll Angle Post-Pulse values for the Higher Brake Force tests were slightly higher on average (9.0 versus 8.5 deg) even though the Lower Brake Force tests produced two-wheel lift at a slightly lower speed (46.1 versus 47.7 mph). The Peak Lateral Acceleration Post-Pulse values were only slightly higher on average for the Higher Brake Force tests (0.91 versus 0.89 g).

As was the case with other test results, the Peak Roll Rate and Yaw Rate Pre-Pulse values were not very different for the higher and lower brake force tests (Table 10.3). The Roll Rate and Yaw Rate Dips due to Pulse were greater for the Higher Brake Force tests. The Peak Roll Rate Post-Pulse for the Higher Brake Force tests was almost twice as high as those for the Lower Brake Force tests (21.5 versus 11.1 deg/sec). The Peak Yaw Rates Post-Pulse occur well after the pulse and were not very different for the two brake force levels.

<u>10.1.3 Variable Brake Force Magnitude at Constant Vehicle Speed Test Results</u>

After the Higher and Lower Brake Force with Increasing Speed tests were completed, a limited number of tests were performed with variable brake force with a fixed initial speed of approximately 40 mph. Both Left and Right Steer direction tests were performed. The results for these tests are also given in Tables 10.1 through 10.3. The data is sorted by Pulse-Brake Magnitude.

Even though it was intended that the initial speed be 40 mph for all the tests, the actual initial speeds ranged from 37.4 to 42.5 mph. Even over this larger than expected range, the pre-pulse brake peak values for the various vehicle responses did not have large fluctuations in value. Therefore, it is believed by the authors that comparing the results from all of the tests is appropriate.

Peak Post-Pulse Brake and "Dip" values for various vehicle responses are plotted as a function of pulse brake magnitude in Figures 10.1 through 10.11. Absolute values of vehicle responses are plotted so Left and Right steer values can be more readily compared on the same chart. Linear regression fits of the data are also plotted. Fits for the Left Steer, Right Steer, and the combined data (Fit All) are given. The slope and r^2 values for each linear regression are given in Table 10.4.

Pulse Brake Duration is plotted as a function of Pulse Brake Magnitude in Figure 10.1. The Pulse Brake Duration increases linearly as a function of Pulse Brake Magnitude. The slopes for the Left and Right Steer are similar (1.02E-3 and 0.86E-3 sec/lbf) and the r^2 values are high (0.94 and 0.83). The combined data has an r^2 value of 0.90.

Table 10.4 -- Vehicle Response to Pulse Brake Linear Regression Values

Vehicle Response	Left Steer Regression		Right Steer Regression		Combined Data Regression	
	Slope (__/lbf)	r^2	Slope (__/lbf)	r^2	Slope (__/lbf)	r^2
Pulse Brake Duration (sec)	1.02E-3	0.94	0.86E-3	0.83	0.97E-3	0.90
Decel due to Turn and Brake (g)	2.33E-3	0.93	1.53E-3	0.93	2.10E-3	0.91
Roll Angle Dip (deg)	-0.69E-2	0.69	-1.24E-2	0.89	-0.87E-2	0.71
Peak Roll Angle Post-Pulse (deg)	1.04E-2	0.77	0.45E-2	0.46	0.87E-2	0.61
Cor. Lat. Acc. Dip (g)	-0.84E-3	0.80	-1.17E-3	0.92	-0.96E-3	0.64
Peak Cor. Lat. Acc. Post-Pulse (g)	2.37E-4	0.41	-2.08E-4	0.09	1.00E-4	0.04
Roll Rate Dip (deg/sec)	1.57E-2	0.13	3.91E-2	0.57	2.35E-2	0.23
Peak Roll Rate Post-Pulse (deg/sec)	6.76E-2	0.80	5.53E-2	0.65	6.52E-2	0.59
Yaw Rate Dip (deg/sec)	-9.79E-3	0.01	0.23E-3	0.83	-2.73E-3	0.11

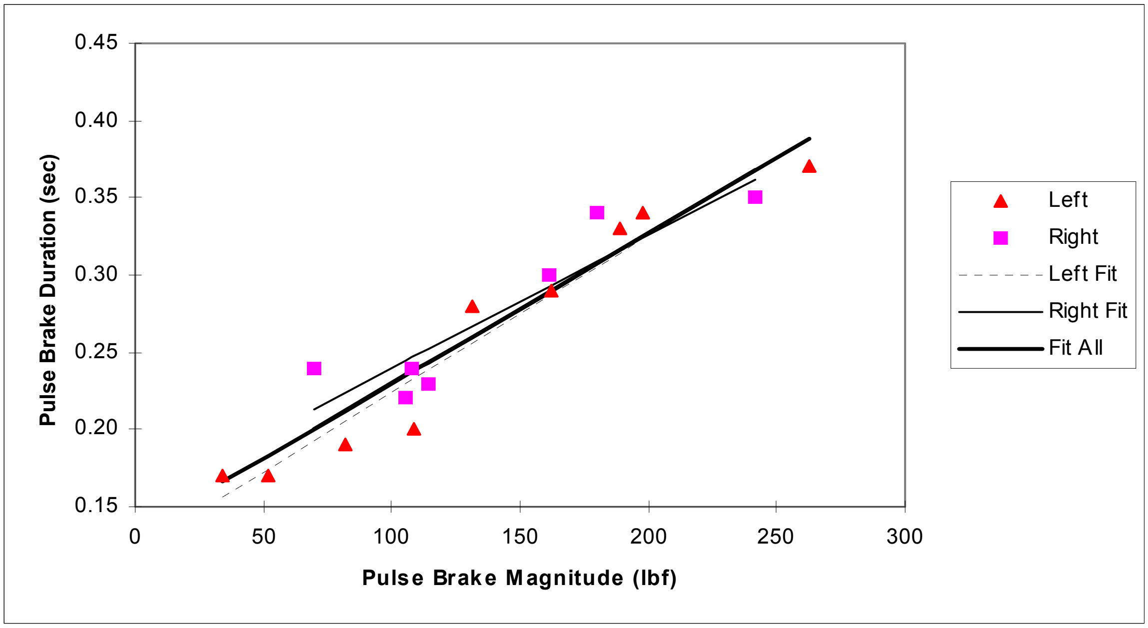


Figure 10.1: Pulse Brake Duration as a Function of Pulse Brake Magnitude

The Deceleration due to Turn and Brake is plotted in Figure 10.2. As would be expected, the Deceleration increases with increasing Pulse Brake Magnitude. The Left Steer slope is greater than that for the Right Steer (2.33E-3 versus 1.53E-3 g/deg). It should be noted that fewer tests were done for the Right Steer direction and there were several tests bunched toward the lower mid-portion of the Pulse Brake Magnitude range of values (105 to114 lbf). A few more tests were performed in the Left Steer direction and these tests were more evenly distributed throughout the range of values. The Left Steer direction also had a slightly greater range of values. The r^2 value for both directions is 0.93. The r^2 value for the combined data is 0.91.

Roll Angle Dip values are plotted in Figure 10.3. It should be noted when looking at "Dip" values that the vehicle response starts at a high level before the pulse and then decreases in magnitude as the pulse is applied. A larger dip is then noted by a smaller magnitude for the vehicle response being measured. The only exception to this for the vehicle responses being examined in this section is roll rate. Roll rate to decrease (larger dip) with increasing brake effort. The slopes of the Left and Right steer regressions

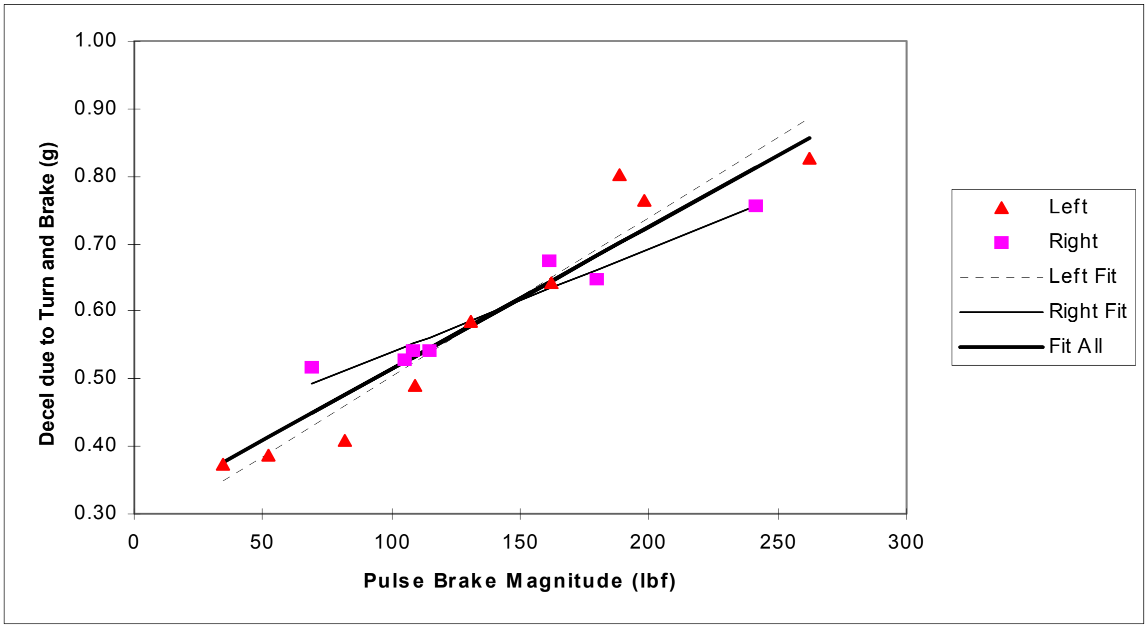


Figure 10.2 -- Peak Deceleration due to Turn and Pulse Brake as a Function of Pulse Brake Magnitude

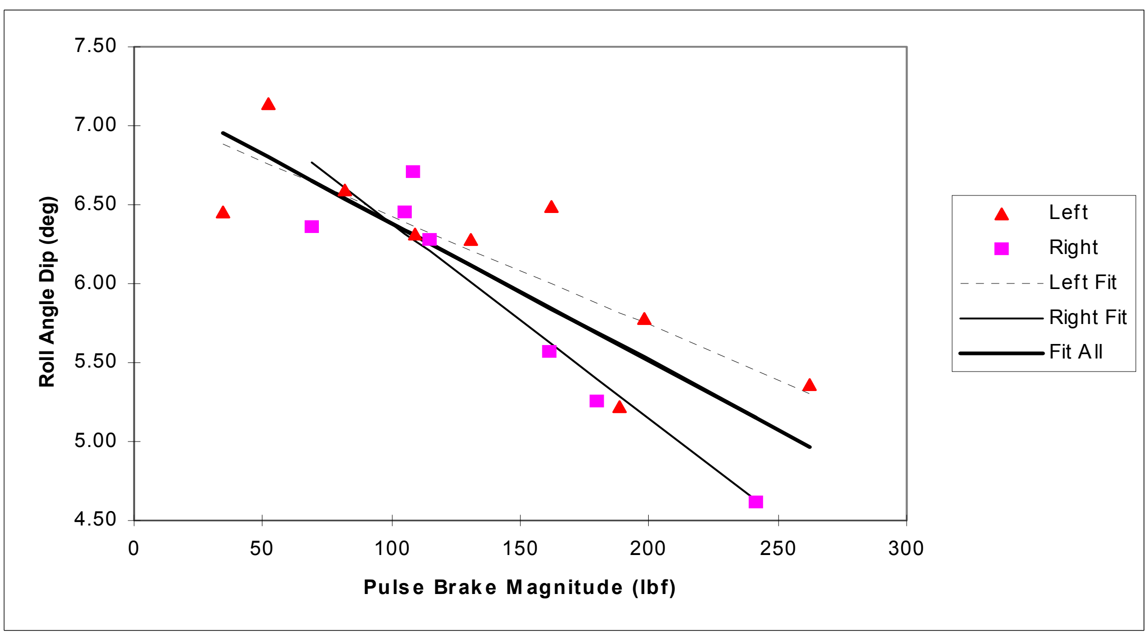


Figure 10.3 -- Roll Angle Dip due to Pulse Brake as a Function of Pulse Brake Magnitude

are relatively different (-0.69E-2 and -1.24E-2 deg/lbf), but have the same trend. The r^2 values are 0.69 and 0.89 respectively. The combined data have an r^2 of 0.071.

The Peak Roll Angle Post-Pulse values are given in Figure 10.4. The Peak Roll Angle Post-Pulse values increase with Pulse Brake Magnitude. The slopes for the Left and Right steer are somewhat different and the data are relatively scattered (r^2 values of 0.77 and 0.46, respectively, with a combined r^2 of 0.61). The Peak Roll Angle Post-Pulse values also appear to plateau with approximately 200 pounds-force applied to the brake pedal. This data suggests that a 200 pound-force Pulse Brake Magnitude would be appropriate for use in future research.

The Corrected Lateral Acceleration Dip values are plotted in Figure 10.5. The magnitude of the Dip gets larger (lower values) with increasing Pulse Brake Magnitude. The slopes of the Left and Right Steer Regressions are fairly similar (-0.84E-3 and -1.17E-3, but the Left Steer values are higher than the Right Steer values. This is consistent with the Peak Corrected Lateral Acceleration Pre-Pulse values as well and therefore is not surprising. The r^2 values are fairly high for the Left and Right Steer regressions (0.80 and 0.92 respectively), but for the combined data the r^2 is lower (0.64) in part due to the Left Steer values being higher than those for the Right Steer.

The Peak Corrected Lateral Acceleration Post-Pulse Brake values are plotted in Figure 10.6. These values are quite scattered (r^2 values of 0.41 and 0.09 for Left and Right Steer respectively). The Left Steer data tends to increase slightly with Pulse Brake Magnitude while the Right Steer data tends to decrease slightly. The trend for the Right Steer data is overly influenced by Test 369 (180 lbf and 0.82 g). This data point is an anomaly for such a high Pulse Brake Magnitude. Examining the results in Table 10.2 shows that the Pre-Pulse and Post-Pulse Corrected Lateral Acceleration Values are very similar for this test (0.81 and 0.82 g). Generally for this high a Pulse Brake Magnitude the Post-Pulse values are more than just 0.01 g higher than the Pre-Pulse values.

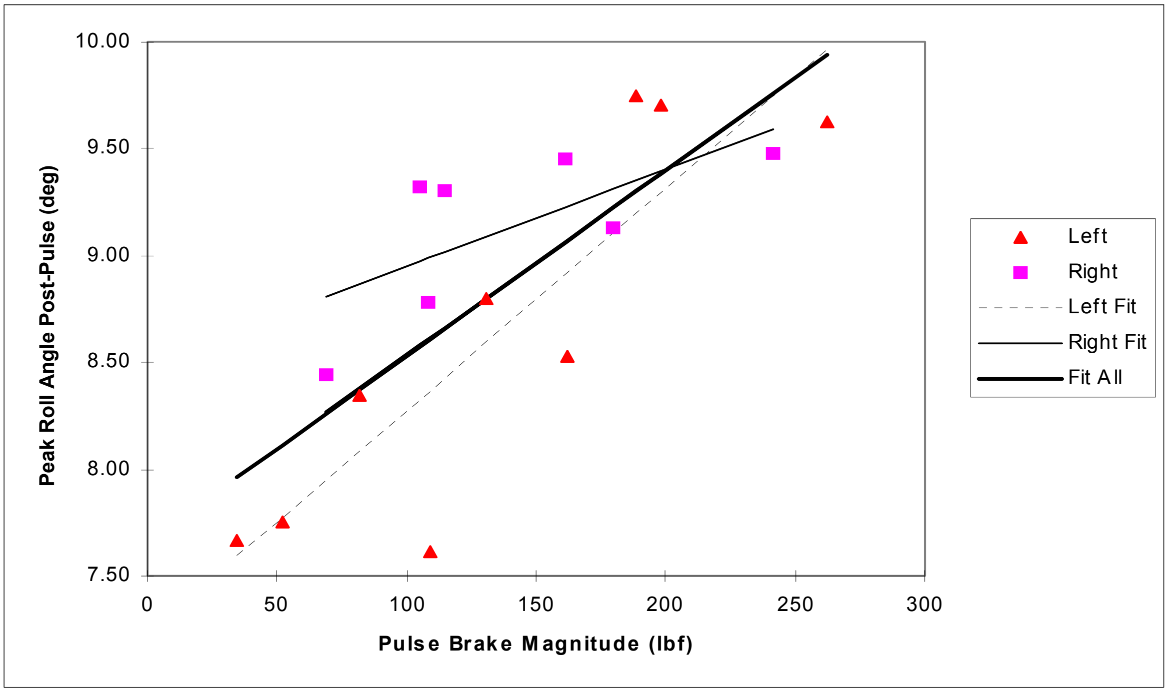


Figure 10.4 -- Peak Roll Angle Post-Pulse Brake as a Function of Pulse Brake Magnitude

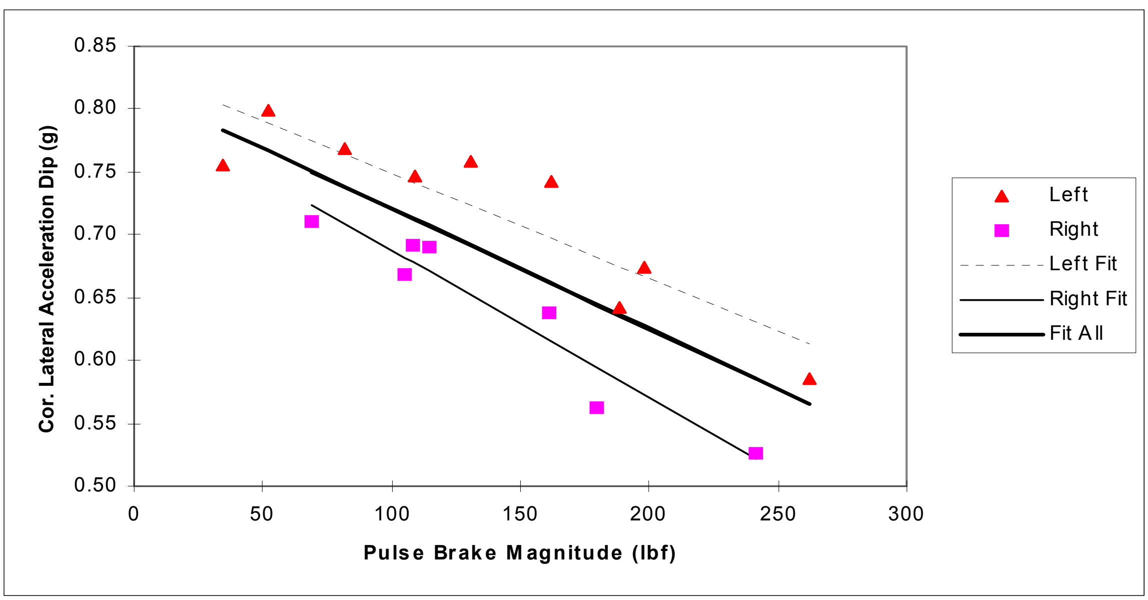


Figure 10.5 -- Corrected Lateral Acceleration Dip due to Pulse Brake as a Function of Pulse Brake Magnitude

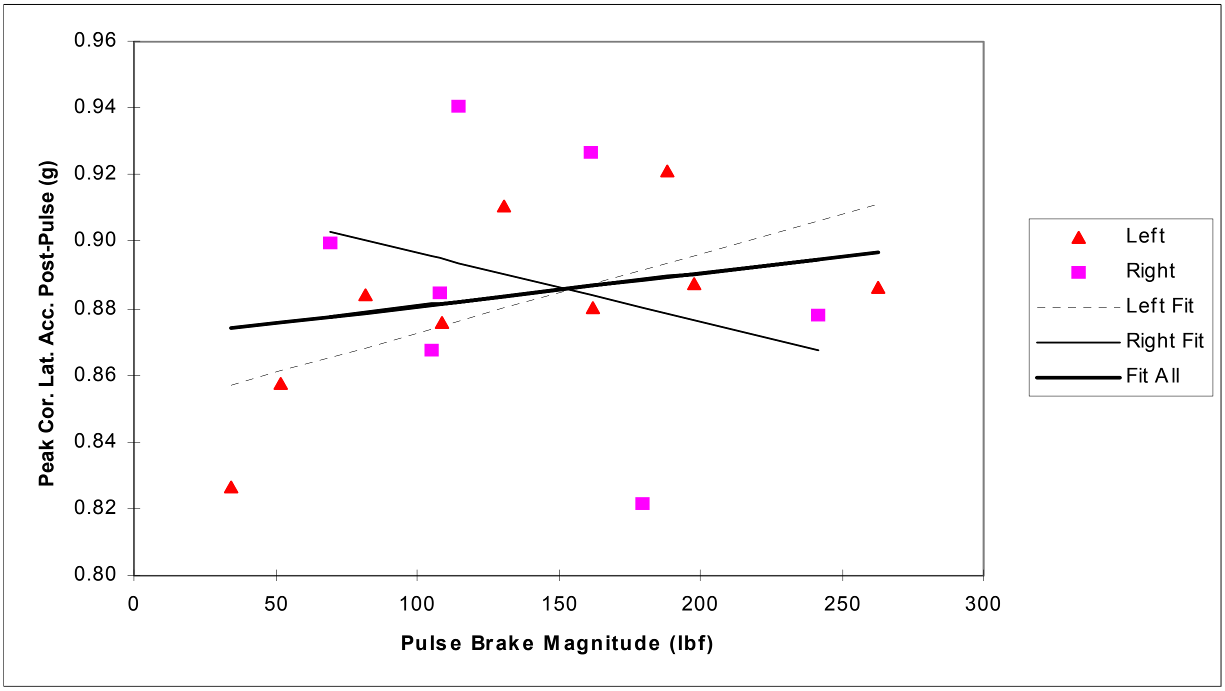


Figure 10.6 -- Peak Corrected Lateral Acceleration Post-Pulse Brake as Function of Pulse Brake Magnitude

The corrected lateral acceleration data traces for Test 369 and Test 371 are plotted in Figure 10.7. In Test 371, the lateral acceleration peaks tend to increase after the pulse brake is applied (following the dip in lateral acceleration). This was not the case in Test 369. The timing of the Pulse Brake relative to the steering input are different for these two tests and may explain some of the differences. The timing of the Pulse Brake appears to have influenced the Roll Rate Dip values.

The Roll Rate Dip values are plotted in Figure 10.8. These values are quite scattered (r^2 values of 0.13 and 0.57 for Left and Right Steer respectively). This might be due to the timing of the pulse-brake relative to the steering input. The roll rate has an under-damped oscillatory response after the steering input has been applied. As is discussed below, this is thought to be due to the timing of the brake pulse. It is expected that if a brake pulse is timed to occur at a trough that the roll rate response may be quite different than if it were timed to occur at a peak.

The effect of Pulse Brake timing on Roll Rate response can be examined by studying the results presented in Figure 10.10. The Pulse Brake and Roll Rate time histories are given for Tests 372 and 375.

Tests 372 and 375 had similar Pulse Brake Magnitudes (114 and 108 lbf respectively) and Pulse Brake Durations (0.24 and 0.22 sec respectively). The Roll Rates for the two tests are very similar up to the point of Pulse Brake application. The Pulse Brake for Test 375 occurs as the vehicle is starting a second roll oscillation. The Pulse Brake for Test 372 occurs slightly later at the (negative) peak of the second oscillation. The Roll Rate Dip values (positive peaks after each Pulse Brake) are very different for these two tests (9.7 deg/sec for Test 372 and 3.9 deg/sec for Test 375). The Peak Roll Rate Post-Pulse Brake values (immediately after pulse and overall) are also higher for Test 372. Since the Roll Rate responses are very similar up to the point of Pulse Brake application and the Pulse Brake Magnitudes and Durations are very similar, it appears that the Pulse Brake affected the Roll Rate response of the vehicle. The effect of this timing could be better studied and understood with a brake pulse actuator that had roll rate control feedback or with computer modeling/simulation.

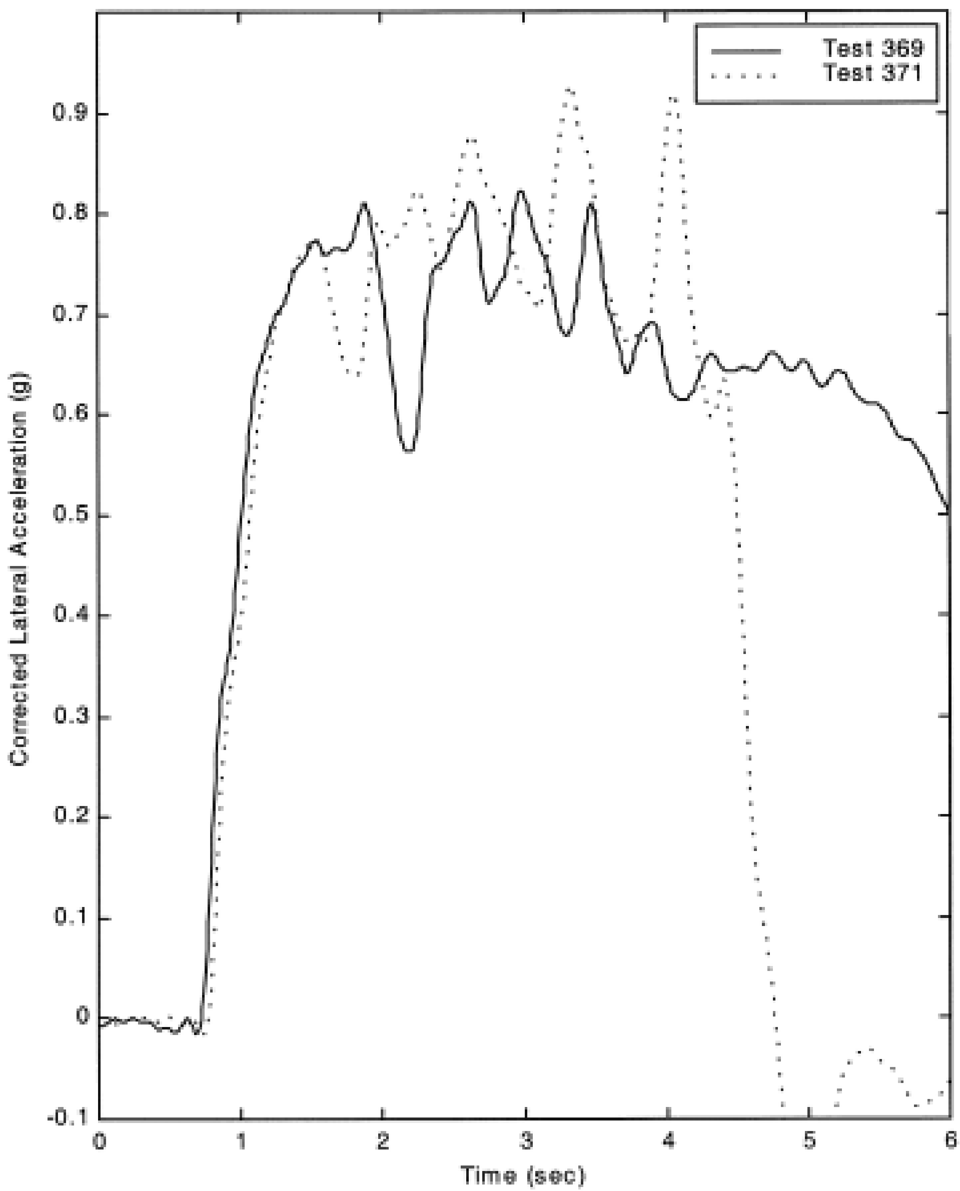


Figure 10.7 -- Comparison of Toyota 4Runner J-Turn with Pulse Brake Using the Steering Controller Tests 369 and 371 - Corrected Lateral Acceleration

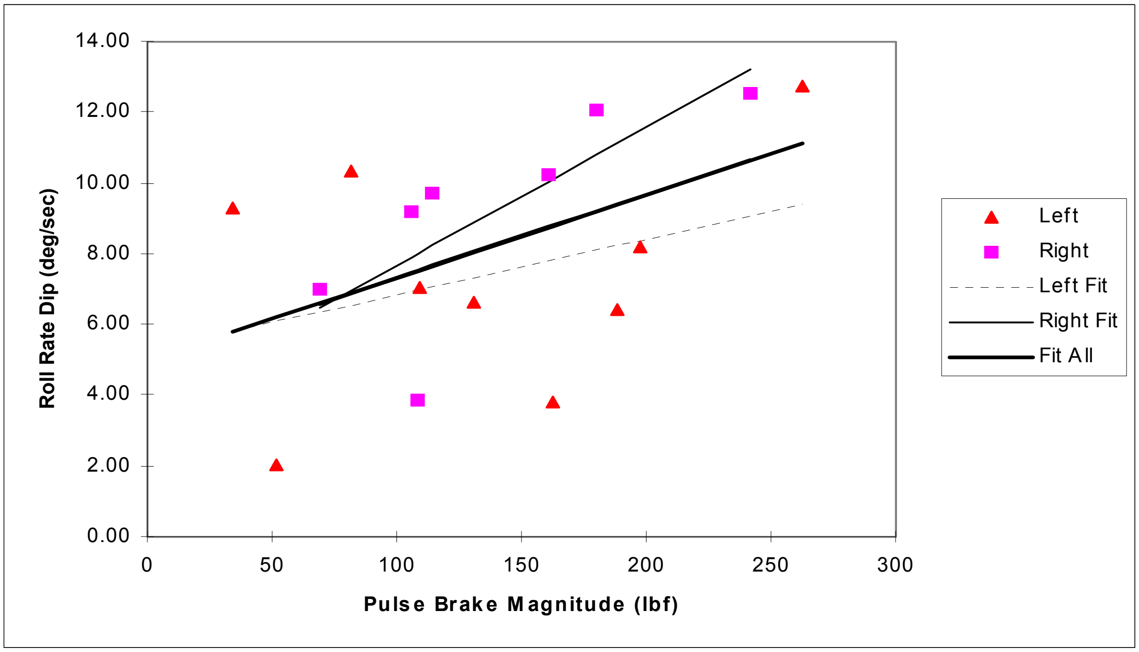


Figure 10.8 -- Roll Rate Dip due to Pulse Brake as a Function of Pulse Brake Magnitude

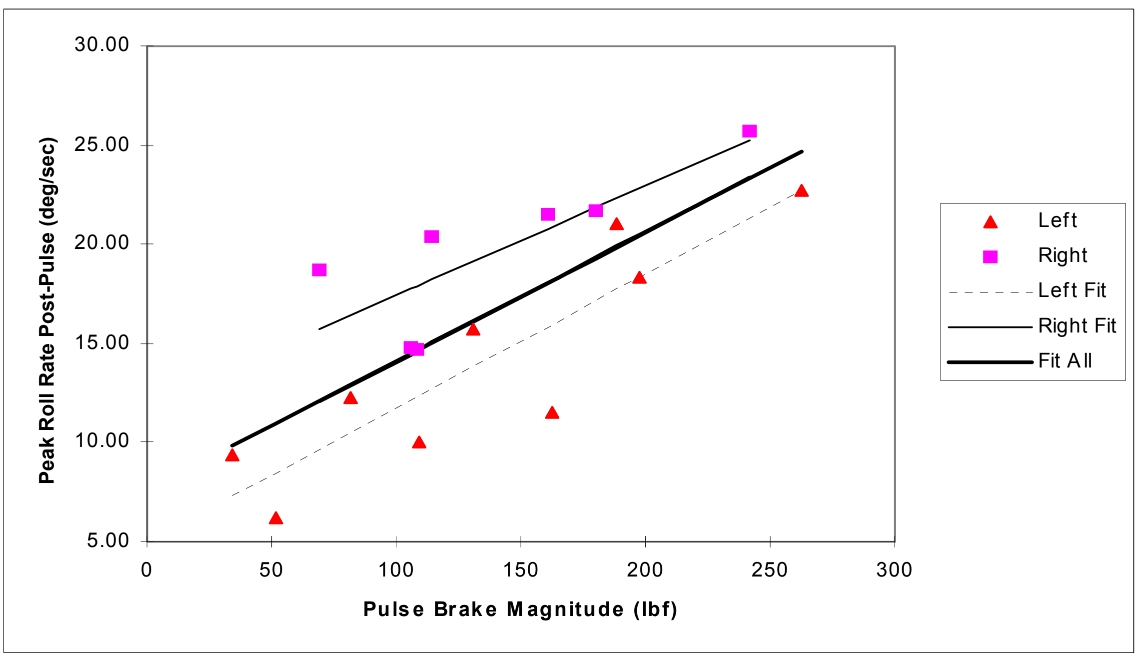


Figure 10.9 -- Peak Roll Rate Post-Pulse Brake as a Function of Pulse Brake Magnitude

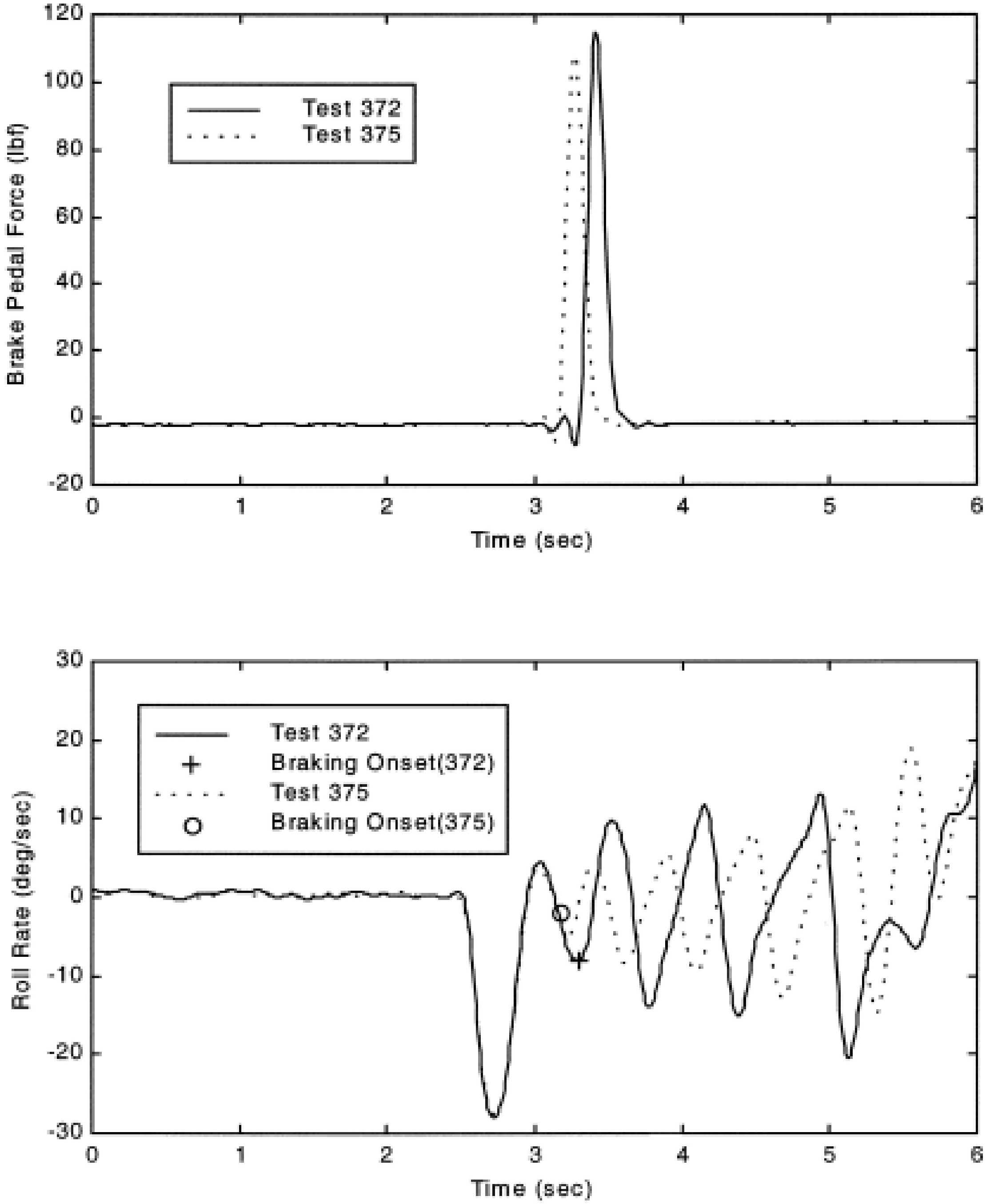


Figure 10.10 -- The Effect of Pulse Brake Timing on Roll Rate Response

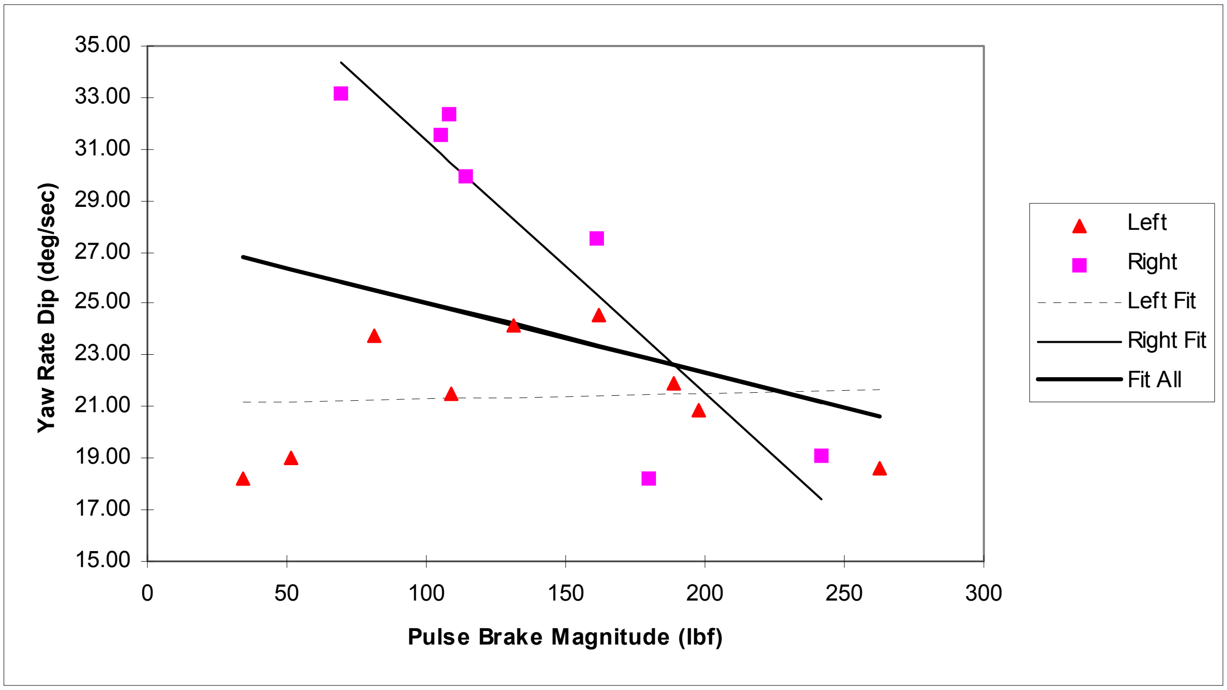


Figure 10.11 -- Yaw Rate Dip due to Pulse Brake as a Function of Pulse Brake Magnitude

The Yaw Rate Dip values due to the Pulse Brake are plotted in Figure 10.11. For Right Steer, the Yaw Rate Dip increases with greater brake effort. The Left Steer values start out with a relatively high Yaw Rate Dip (again a small value), which at first decreases (higher value) and then increases with Pulse Brake Magnitude. It is not clear why the Left Steer Yaw Rate Dips would be so high at a low Pulse Brake Magnitude. This result is counter intuitive. The Right Steer Linear Regression had a relatively high r^2 value (0.83), while the Left Steer did not (0.01). The Peak Yaw Rates Post-Pulse occur well after the Pulse Brake is applied and therefore were not examined further.

10.1.4 J-Turn Steering Controller Repeatability and Comparison to Driver Inputs

Examining the Peak and Average Handwheel Rates in Table 10.1 shows that these values were very consistent. The handwheel angle traces for Tests 345 through 353 are plotted in Figure 10.12. There is very little difference in these traces up to the point where the driver takes control back from the steering controller. The time the driver takes control does vary from trace-to-trace (approximately 3.5 to 5.0 seconds).

The Peak and Average Handwheel Rates using the controller are generally higher than those for the driver controlled J-Turn tests discussed in Chapter 7. The Peak and Average Handwheel Rates for the Steering Controller were approximately 1150 and 800 deg/sec (Table 10.1). For the driver, these values were approximately 900 and 550 deg/sec (Table 7.1). One of the drivers did achieve a Peak Handwheel Rate of 1129 deg/sec. The highest single test Average Handwheel Rate was 628 deg/sec.

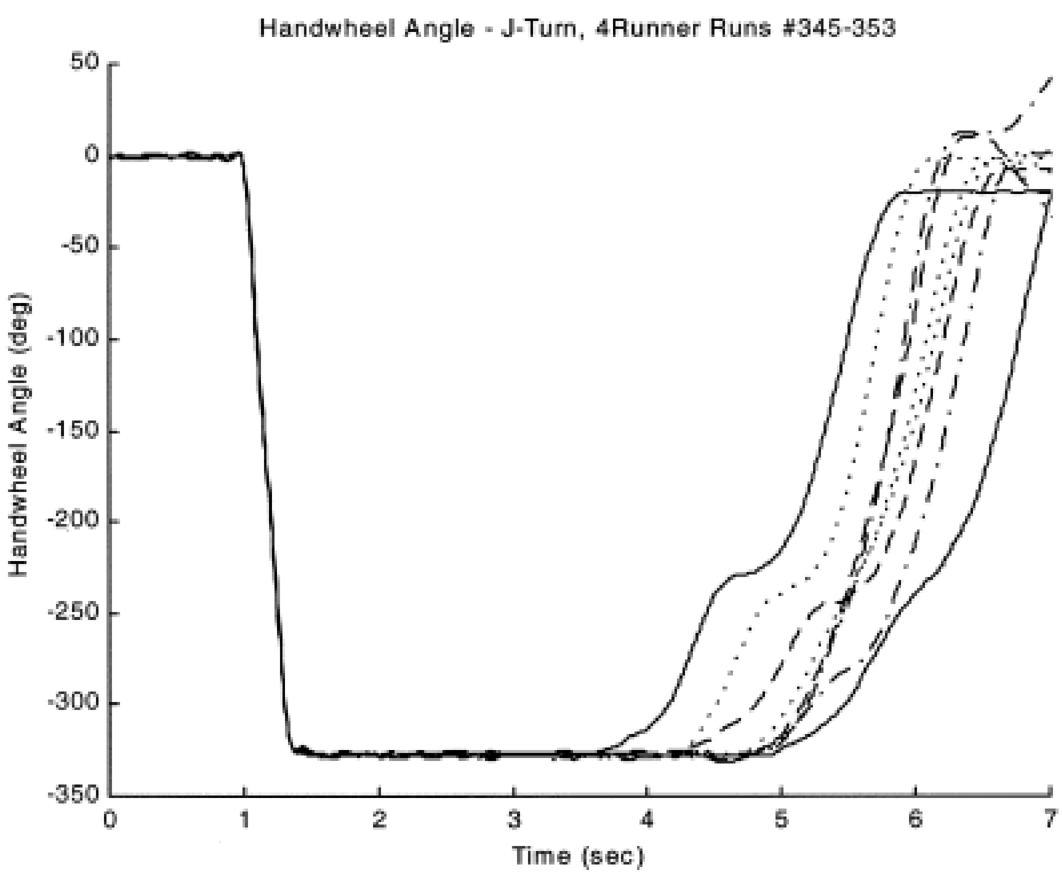


Figure 10.12 -- J-Turn Steering Inputs using the Steering Controller

10.1.5 Summary of J-Turn with Pulse Braking Testing Using the Steering Controller Results

For this first part of this steering controller study, two sets of tests were performed to see the effect of a lower brake pedal force versus a higher brake pedal force on J-Turn with Pulse Braking overall results, i.e., does a lower brake pedal force require a higher speed to achieve two-wheel lift.

For the Higher Brake Force tests that had a similar speed range to those for the Lower Brake Force tests, the Higher and Lower Brake Force values had an average of approximately 220 and 120 pound-force respectively. The Higher Brake Force values had a longer Pulse Brake Duration on average. As would be expected, the Deceleration due to Turn (prior to the brake pulse) for the two sets of data were the same. The Deceleration due to Turn and Brake was approximately 1/3 higher for the Higher Brake Force tests.

The Peak Pre-Pulse vehicle responses were very similar for the two brake force levels. The Dips due to Pulse vehicle responses were greater on average for the Higher Brake Force tests. The Peak Post-Pulse vehicle responses were generally higher for the Higher Brake Force tests. In partaicular, the Peak Roll Angle Post-Pulse was 0.5 degrees larger (9.0 verus 8.5 degrees) for the Higher Brake Force tests. However, counter intuitively, the Lower Brake Force tests produced two-wheel lift at a slightly lower speed.

For the second part of the steering controller study, the test speed was kept constant (approximately 40 mph) and the driver was asked to provide varying levels of brake pedal force. The following values were plotted as a function of Pulse Brake Magnitude: Pulse Brake Duration, Decel due to Turn and Brake, Roll Angle Dip, Peak Roll Angle Post-Pulse, Corrected Lateral Acceleration Dip, Corrected Lateral Acceleration Post-Pulse, Roll Rate Dip, Peak Roll Rate Post-Pulse, and Yaw Rate Dip. Linear regressions for the Left Steer and Right Steer values for each of these variables were calculated.

Pulse Brake Duration, Decel due to Turn and Brake, and Corrected Lateral Acceleration Dip had good correlation for both steer directions (r^2 values greater than or equal to 0.80). For the Left Steer direction, Peak Roll Rate Post-Pulse also had an r^2 value greater than or equal to 0.80. For the Right Steer direction, Roll Angle Dip and Yaw Rate Dip had r^2 values greater than or equal to 0.80.

In agreement with the first part of this study, the Peak Post-Pulse vehicle responses measured during the second part of this study tended to increase with increasing brake pedal force. The increase for Peak Roll Angle (0.87 deg.100 lbf) is more important than that seen for Peak Corrected Lateral Acceleration (0.01 g/100 lbf).

The timing of the Pulse Brake appears to have some influence on results; especially the Roll Rate response. The effect of this timing could be better studied and understood with a brake pulse actuator that had roll rate control feedback or with computer simulation/modeling.

The Peak and Average Handwheel Rates found using the controller were very consistent. The Peak and Average Handwheel Rates using the controller are generally higher than those for the driver controlled J-Turn tests.

The results of this study confirm the Phase I-A finding that 200 pounds-force is a good target value for the brake pulse pedal force. Both Phase I studies found that the peak, post-pulse, roll angle increases with increasing brake pulse pedal force while 200 pounds-force is a reasonable upper limit to the force that can be generated by test drivers in a rapid, pulse-like manner.

10.2 Fishhook Maneuver Test Results and Analysis - Steering Controller Study

Two Fishhook Profile studies were performed using the steering controller. The first examined two steering profiles by running complete Fishhook test sequences so a Lateral Acceleration at Rollover (LAR) could be determined. The second examined two levels of handwheel rate and four levels of pause between the first and second steer with all the tests being conducted at 30 mph. Individual test results are given in Appendix B.

10.2.1 Fishhook Steering Profile Study Number 1

The first steering controller Fishhook Profile study compared two steering profiles by running complete Fishhook test sets so a LAR could be determined. The first profile had a 270 degree initial steer with a 0.25 second pause (dwell time) followed by a steer in the opposite direction to the steering stop. The second profile had a 180 degree initial steer with a 0.5 second dwell time followed by a steer in the opposite direction again to the steering stop. The handwheel rate was 500 deg/sec for both steering profiles.

The LAR values and the speeds required to produce two-wheel lift are given in Table 10.5. The LAR values for the two steering profiles are very similar for the two steer directions. The minimum speed required to produce two-wheel lift are the same for both profiles for the right-left steer combination, but the 180 degree initial steer profile required two more miles per hour to produce two-wheel lift than the 270 degree profile for the left-right steer combination. Repeat test series were not performed so it is not known whether this is within the variability of testing for any particular steering profile or not.

Table 10.5 -- Fishhook Two-Wheel Lift Speed and LAR Values for Two Different Steering Profiles

Steering Profile			Left-Right		Right-Left	
First Steer	Dwell Time (sec)	Second Steer	Speed (mph)	LAR (g)	Speed (mph)	LAR (g)
270	0.25	To Stop	38	0.85	38	0.89
180	0.50	To Stop	40	0.84	38	0.88

The results for similar speed tests for the two Fishhook steering profiles are given in Table 10.6. Two tests for each steering profile are shown. The maximum lateral acceleration, roll rate, yaw rate, and roll angle are given for the first and second steering inputs. Tests 33 and 36 had 270 degrees of initial steer, while Tests 43 and 46 had 180 degrees of initial steer. Tests 33 and 43 had a nominal speed of 32 mph, while Tests 36 and 46 had a nominal speed of 37.5 mph.

The lateral accelerations caused by the first steer are generally lower for the nominal 180 degree steering input, but this is not necessarily the case for the second input. The initial and secondary peak roll rates are very similar for the two inputs. The initial yaw rates are much higher for the 270 degree initial steering input which, when coupled with the higher lateral accelerations, suggests the tires are not saturated at 180 degrees of handwheel angle for this vehicle. The secondary peak yaw rates occur relatively late in the event and are not pertinent. The roll angles caused by the first steer are very similar for the 270 and 180 degree inputs. The roll angles for the second steer are not always higher for one initial steer versus the other.

Table 10.6 -- Steering Profile Differences for 270 and 180 degree Initial Steering Input For Fishhook Testing

Test No.	Speed	First Steer (deg)	Second Steer (deg)	Cor. Lat. Acc. First Peak (g)	Cor. Lat. Acc. Second Peak (g)	Roll Rate First Peak (deg/sec)	Roll Rate Second Peak (deg/sec)	Yaw Rate First Peak (deg/sec)	Yaw Rate Second Peak (deg/sec)	Roll Angle First Peak (deg)	Roll Angle Second Peak (deg)
33	32.0	269	-779	0.73	-0.76	-17.6	36.1	30.8	-46.7	-6.2	7.8
36	37.6	270	-785	0.76	-0.97	-19.2	41.3	31.2	-51.7	-6.6	9.9
43	32.1	180	-762	0.69	-0.78	-17.8	34.1	26.8	-44.2	-6.2	7.4
46	37.4	179	-765	0.73	-0.84	-20.8	40.5	26.2	-40.8	-6.4	8.5

10.2.2 Fishhook Steering Profile Study Number 2

For the second Fishhook Profile study, two levels of handwheel rate were used (500 and 750 deg/sec) and four levels of dwell time between initial and second steer (0, 0.25, 0.5, and 1.0 sec). Four replications were conducted and the tests were performed in a random order for each replication. All of the testing was conducted at 30 mph. The steering magnitudes were 270 degrees for the initial steer and 600 degrees (after returning to zero) for the steering reversal.

A review of the collected data showed that the inputs for the 500 deg/sec handwheel rate and 0.25 second dwell time (Program 2 in Table 6.5) was not performed as expected and so the data for this combination was not used in the analysis.

An analysis of variance was performed using the statistical software package SAS. The input variables were initially handwheel rate, dwell time, and replication. Replication was later dropped because it was not found to be a significant influence on results. This suggests that tire wear, road surface conditions, and weather conditions did not have an influence on results for this Fishhook Profile study. The output variables studied were the initial and secondary peak values for corrected lateral acceleration, roll angle, roll rate, and yaw rate.

The SAS routine looked at the influence of handwheel rate, dwell time, and the interaction of handwheel rate and dwell time on results. If the probability of influence for a particular input variable was found to be statistically significant ($p < 0.05$) the p-value for that input variable (or interaction between variables) is given in the appropriate box(es) next to the studied output variables in Table 10.7. If there was more than one statistically significant input variable, the one with the lower p-value has a stronger influence on the output variable.

For the peak corrected lateral acceleration resulting from the initial steer (Cor. Lat. Acc. 1), handwheel rate, dwell time, and the interaction of handwheel rate and dwell time were all statistically significant, with dwell time and interaction of handwheel rate and dwell time being more significant than handwheel rate (0.0001 versus 0.0038). The meaning of these results can best be interpreted by examining the peak corrected lateral acceleration mean values for the different combinations of input variables.

The output variable mean values and number of observations for the two handwheel rates and four dwell time levels are given in Table 10.8. The number of observations is also listed. The output variable mean values and standard deviations for each combination of handwheel rate and dwell time are given in Appendix C. As stated previously and as shown by the number of observations listed in Table 10.8, the 500 deg/sec handwheel rate and 0.25 second dwell time combination was not evaluated.

The mean values for peak corrected lateral acceleration resulting from the initial steer are very similar for the two handwheel rates (0.70 and 0.69 g), but they vary quite a bit for the dwell time duration (0.61 to 0.74 g). This is a clear indication that dwell time duration had a much more significant effect than handwheel rate on the initial peak corrected lateral acceleration. The mean values increased with increasing pulse duration, although there is not much difference between the 0.5 second dwell time and the 1.0 second dwell time (0.73 versus 0.74 g). It is somewhat surprising that handwheel rate was found to be a significant variable given the similar mean values. The lack of data for the 500 deg/sec handwheel rate and 0.25 second dwell time combination may have artificially made these mean values appear to be closer than they really are.

Table 10.7 -- Statistically Significant Handwheel Input Variables for Fishhook Test Results

Output Variable	Input Variables p-Values		
	Handwheel Rate	Dwell Time	Interaction of Handwheel Rate and Dwell Time
Cor. Lat. Acc. 1	0.0038	0.0001	0.0001
Cor. Lat. Acc. 2	0.0002	0.0086	0.0313
Roll Angle 1		0.0006	
Roll Angle 2	0.0005		
Roll Rate 1	0.0001		
Roll Rate 2	0.0001	0.0001	0.0001
Yaw Rate 1	0.0007	0.0001	
Yaw Rate 2			

Table 10.8 -- Output Mean Values for Different Levels of Handwheel Rate and Dwell Time

Input Variable	Number of Observations	Output Variable Mean Values							
		Cor. Lat. Acc. First Peak (g)	Cor. Lat. Acc. Second Peak (g)	Roll Angle First Peak (deg)	Roll Angle Second Peak (deg)	Roll Rate First Peak (deg/sec)	Roll Rate Second Peak (deg/sec)	Yaw Rate First Peak (deg/sec)	Yaw Rate Second Peak (deg/sec)
Handwheel Rate									
500	12	0.70	-0.79	-6.6	7.5	-16.7	26.1	30.8	-49.8
750	16	0.69	-0.83	-6.6	8.1	-22.3	35.7	31.8	-49.8
Dwell Time									
0.00	8	0.61	-0.83	-6.4	8.0	-19.3	32.4	30.2	-49.8
0.25	4	0.70	-0.84	-6.5	8.3	-22.4	37.5	31.9	-49.4
0.50	8	0.73	-0.81	-6.7	7.8	-19.6	31.6	31.9	-49.9
1.00	8	0.74	-0.79	-6.7	7.5	-19.5	27.7	31.7	-49.9

As seen in Table 10.7, handwheel rate, dwell time, and the interaction of handwheel rate and dwell time were all statistically significant variables for the peak corrected lateral acceleration after the steering reversal (Cor. Lat. Acc. Second Peak). Examining the mean values in Table 10.8, the 750 deg/sec handwheel rate produced larger lateral accelerations than the 500 deg/sec handwheel rate. The 1 second dwell time seems to reduce the peak lateral acceleration slightly compared to the other pause levels. The 0.25 second dwell time mean value may be artificially high due to the lack of data for the 500 deg/sec handwheel rate.

Again from Table 10.7, the initial roll angle peak is only influenced by dwell time. As shown in Table 10.8, the mean values for the two handwheel rates are identical for the initial roll angle peak (-6.6 deg). The mean values increase slightly with dwell time, up to 0.5 seconds and then level off.

The roll angle peak after the steering reversal is only influenced by handwheel rate using $p < 0.05$. The p-value for dwell time was 0.08 which suggests that dwell time is nearly significant for this output variable. The mean value for the 500 deg/sec handwheel rate was 7.5 degrees versus 8.1 degrees for the 750 deg/sec handwheel rate. The mean values for dwell time have a similar range, but again the 0.25 second dwell time value is artificially high due to the lack of observations for the 500 deg/sec handwheel rate. The mean values for the 0 and 0.50 second dwell time are fairly similar, but the mean value for the 1 second dwell time is slightly lower.

The initial roll rate is only influenced by handwheel rate. The mean initial roll rate for the 500 and 750 deg/sec handwheel rates are -16.7 and -22.3 deg/sec respectively. The 0.25 second dwell time mean value is artificially high compared to the other dwell time values due to the lack of 500 deg/sec handwheel rate tests for this dwell time value. The roll rate peak after the steering reversal is influenced by the handwheel rate, dwell time, and interaction of handwheel rate and dwell time. The mean roll rate for the 750 deg/sec handwheel rate is much higher than that for the 500 deg/sec handwheel rate (35.7 and 26.1 deg/sec respectively). The roll rate peak after the steering reversal tends to decrease as dwell time increases (again the 0.25 second dwell time mean value is artificially high).

The initial yaw rate mean values appear to be influenced by handwheel rate and dwell time (Table 10.7). From Table 10.8, the mean values for the two handwheel rates are 1 deg/sec different (30.8 and 31.8

deg/sec). The mean values range from 30.2 to 31.9 deg/sec for the range of dwell time values. While the p-values are less than 0.05, it is not clear that these relatively small differences in mean yaw rate are truly significant. It is interesting to note that the yaw rate due to the steering reversal was not affected by any of the input variables. An examination of the data shows that this peak yaw rate occurs well after the second steering input has been made and is probably related to the vehicle slowing down with a large steering angle maintained from the steering reversal.

10.2.3 Fishhook Steering Controller Repeatability

Results from Fishhook Steering Controller Study 2 lend themselves to examining the repeatability of the inputs to the steering system supplied by the controller and the corresponding vehicle responses. For each test condition, four replications were run. An examination of the initial speeds showed that Program Number 5 (0.50 second dwell time duration and 750 deg/sec steering rate) had the least amount of scatter in the initial test speed values. These values ranged from 30.1 to 30.5 mph.

The handwheel angle and vehicle speed channels for these four tests are plotted in Figure 10.13. The handwheel angles lay right on top of each other up until the steering reversal has been completed. Over the flat part near -600 degrees there is some variation between the tests. It is believed that this is more a function of the "unwrap" routine than it is differences in the actual input. The initial handwheel pot on the steering machine only had a range of +/-360 degrees. This led to the handwheel trace having large jumps in value as the pot wrapped past +/-360 degrees. The channel had to be unwrapped. Several processing routines were used to unwrap the data, but all gave some variation between the tests. The vehicle speed channels are very similar and show that the driver released the throttle near the same time for each test.

The lateral acceleration and roll angle traces for these tests are plotted in Figure 10.14. The lateral acceleration traces for all four tests are very similar up to approximately 3 seconds. There are some minor differences between the tests as the vehicle goes through small oscillations past 3 seconds, but the differences are relatively minor. The same can be said for the roll angle traces presented in the lower box in Figure 10.14.

The roll rate and yaw rate traces are plotted in Figure 10.15. As was the case with lateral acceleration and roll angle, these traces are very similar up to approximately 3 seconds. There are some differences between the tests as the vehicle goes through small oscillations. Test 262 seems to be the most different from the other tests, especially for the roll rate trace.

The traces presented in Figures 10.13 through 10.15 clearly show that the steering controller produces very repeatable steering inputs and that the corresponding vehicle responses can be very repeatable as well.

10.2.4 Summary of Fishhook Testing Using the Steering Controller Results

The first steering controller Fishhook Profile study compared two steering profiles by running complete Fishhook test sets so an appropriate LAR could be determined. The first profile had a 270 degree initial steer with a 0.25 second dwell time followed by a steer in the opposite direction to the steering stop. The second profile had a 180 degree initial steer with a 0.5 second dwell time followed by a steer in the opposite direction again to the steering stop. The handwheel rate was 500 deg/sec for both steering profiles.

The LAR values for the two steering profiles are very similar for the two steer directions. The minimum speed required to produce two-wheel lift are the same for the right-left steer direction, but the 180 degree initial steer profile required two more miles per hour to produce two-wheel lift than the 270 degree profile. Repeat test series were not performed so it is not known whether this is within the variability of testing for any particular steering profile or not.

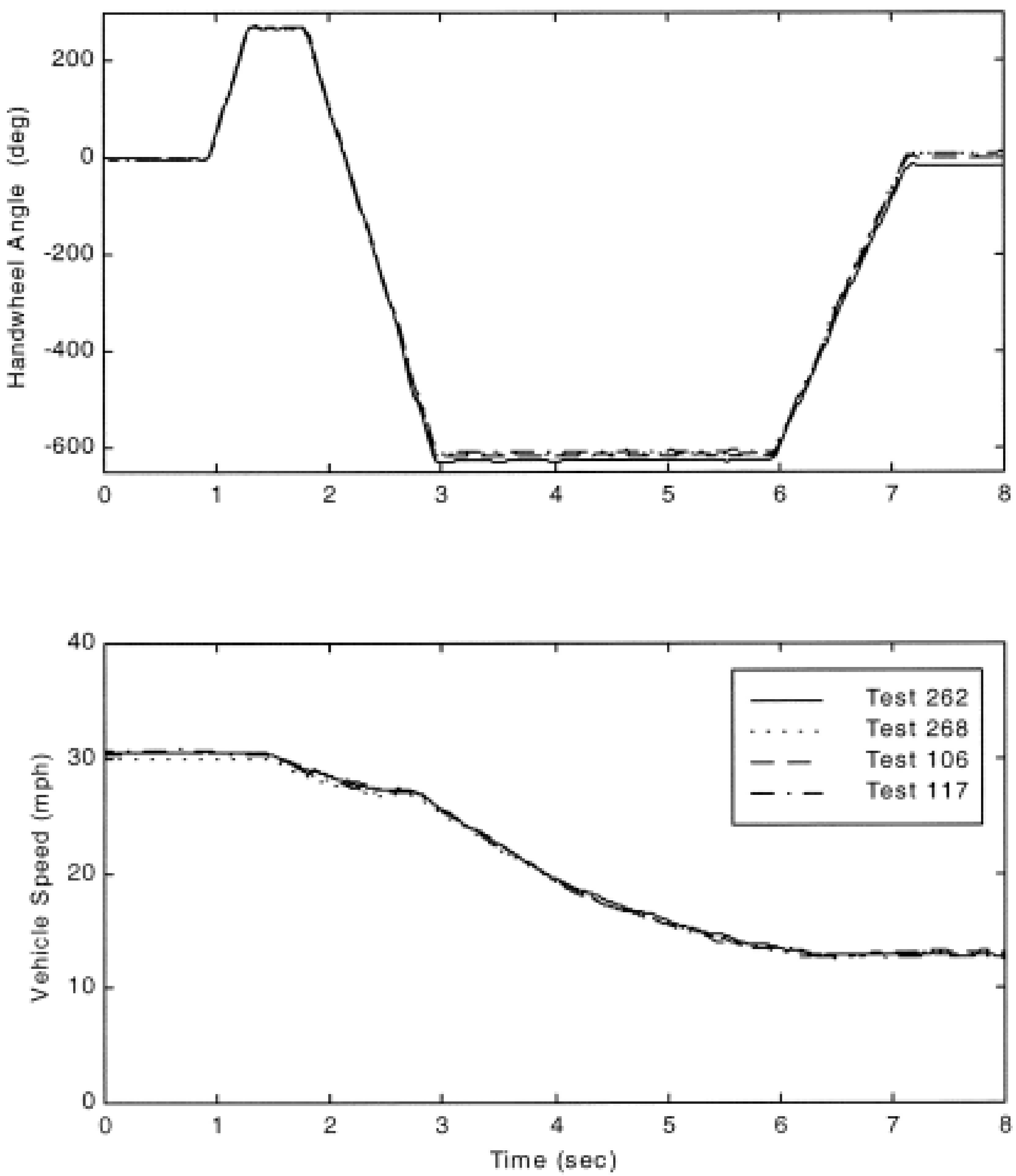


Figure 10.13 -- Fishhook Repeatability Tests with the Steering Controller - Handwheel Angle And Vehicle Speed

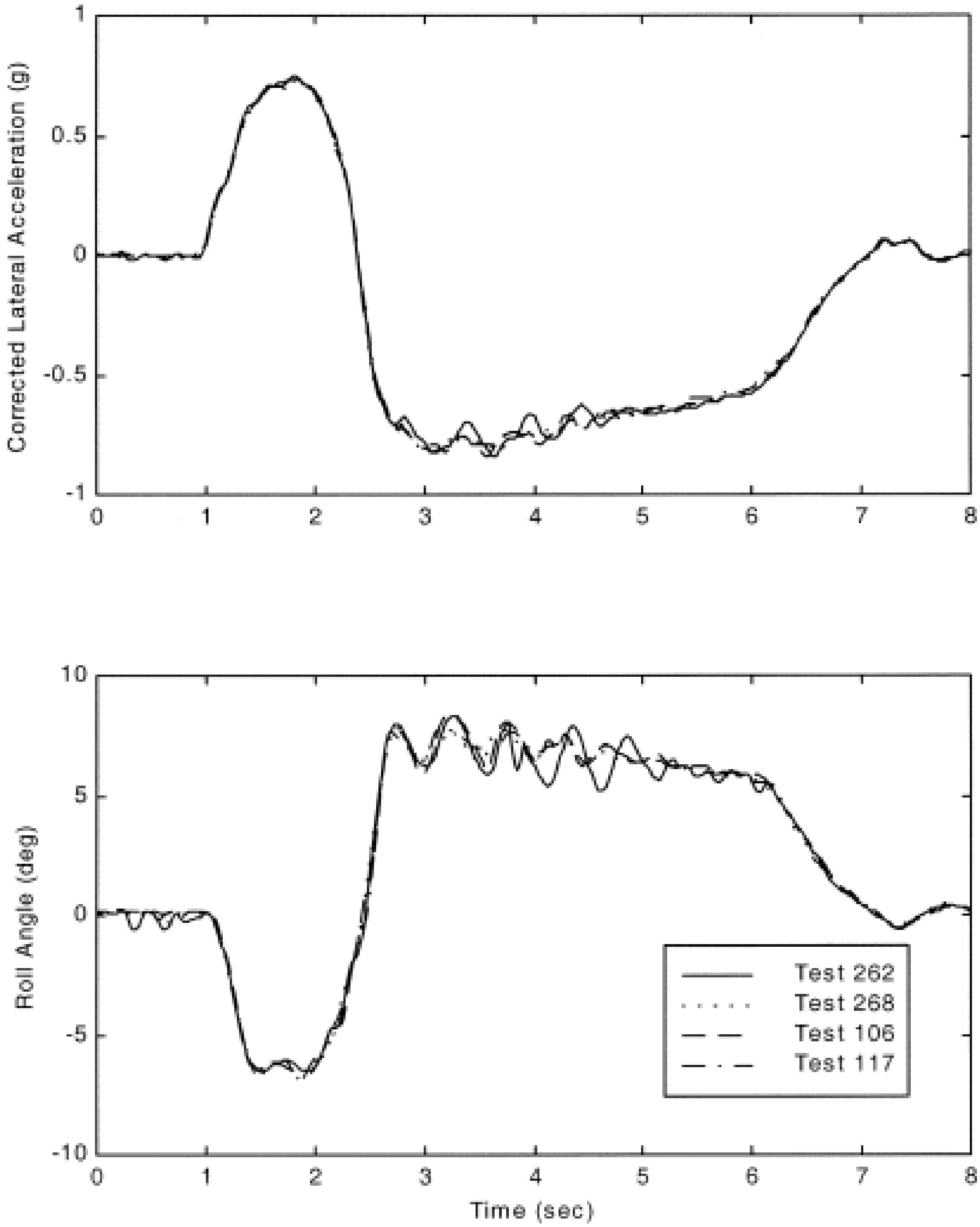


Figure 10.14 -- Fishhook Repeatability Tests with the Steering Controller - Lateral Acceleration and Roll Angle

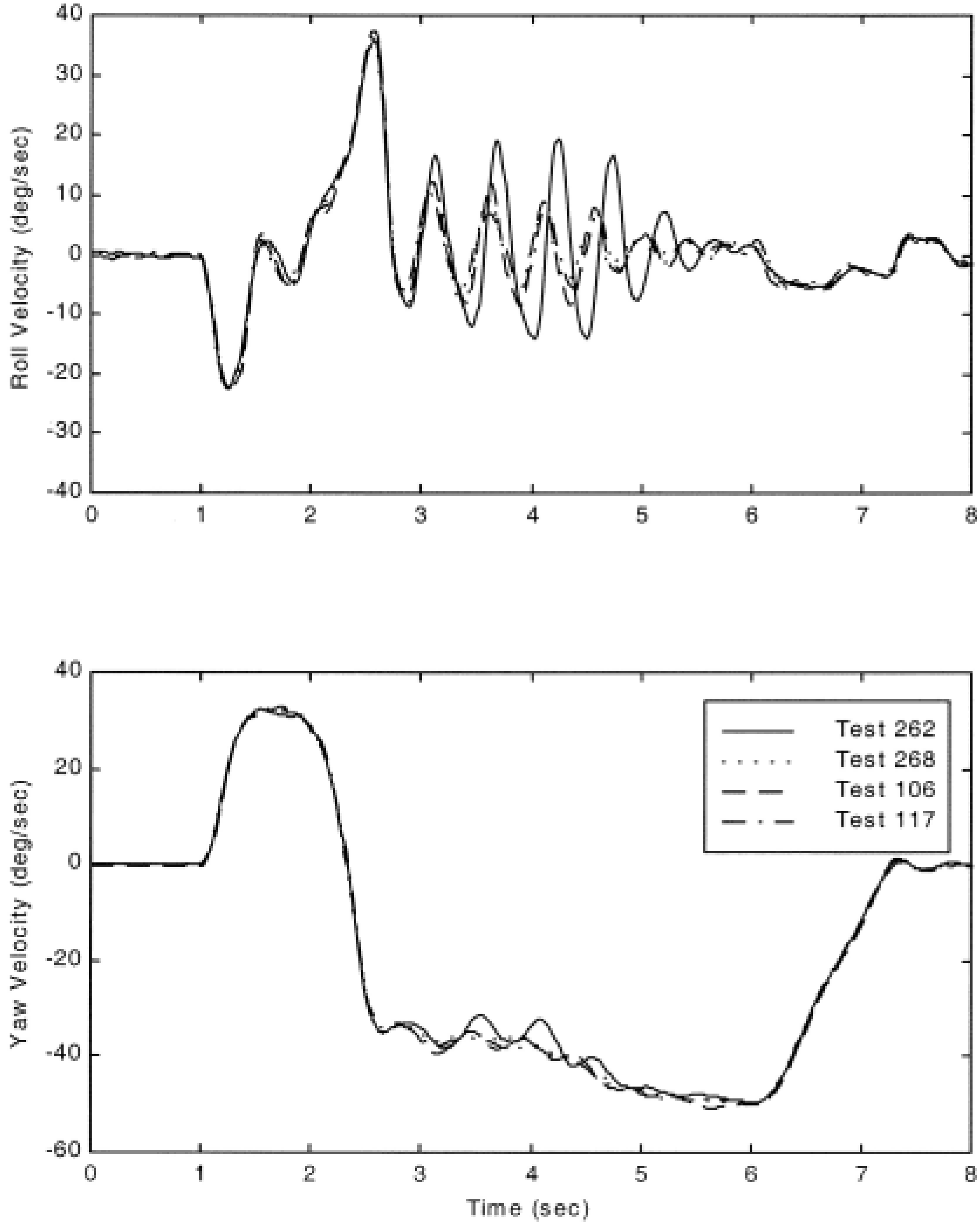


Figure 10.15 -- Fishhook Repeatability Tests with the Steering Controller - Roll Velocity and Yaw Velocity

The lateral accelerations caused by the first steer are generally lower for the nominal 180 degree steering input, but this is not necessarily the case for the second input. The initial and secondary peak roll rates are very similar for the two inputs. The initial yaw rates are much higher for the 270 degree initial steering input which, when coupled with the higher lateral accelerations, suggests the tires are not saturated at 180 degrees of handwheel angle for this vehicle. The roll angles caused by the first steer are very similar for the 270 and 180 degree inputs. The roll angles for the second steer are not always higher for one initial steer versus the other.

For the second Fishhook Profile study, two levels of handwheel rate were used (500 and 750 deg/sec) and four levels of dwell time between initial and second steer (0, 0.25, 0.5, and 1.0 sec). Four replications were conducted and the tests were performed in a random order for each replication. All of the testing was conducted at 30 mph. The steering magnitudes were 270 degrees for the initial steer and 600 degrees (after returning to zero) for the steering reversal.

An analysis of variance was performed using the statistical software package SAS. The input variables were initially handwheel rate, dwell time, and replication. Replication was later dropped because it was not found to be a significant influence on results. This suggests that tire wear, road surface conditions, and weather conditions did not have an influence on results for this Fishhook Profile study. The output variables studied were the initial and secondary peak values for corrected lateral acceleration, roll angle, roll rate, and yaw rate.

The SAS routine looked at the influence of handwheel rate, dwell time, and the interaction of handwheel rate and dwell time on results. One or more of these variables was found to have an influence on almost all of the initial and secondary peak vehicle response values. In very broad terms, the 750 deg/sec handwheel rate generally produced greater peak values than the 500 deg/sec rate. Also in very broad terms, the 0.25 and 0.50 second dwell time values tended to produce greater peak values than the 0 and 1 second dwell time values.

Results from Fishhook Steering Controller Study 2 were examined to assess the repeatability of the inputs to the steering system supplied by the controller and the corresponding vehicle responses. Four tests were compared. These tests were selected because they used the same handwheel input and had very similar initial test speed values (30.1 to 30.5 mph). The results show that the steering controller produces very repeatable steering inputs and that the corresponding vehicle responses were very repeatable.

10.3 Resonant Steer Maneuver Test Results and Analysis - Steering Controller Study

The resonant steer test first requires that the roll natural frequency for the vehicle be determined. This can be done using either a pulse steer or sinusoidal sweep maneuver.

10.3.1 Pulse Steer Test Results

Pulse steering tests were performed using the steering controller and the 1990 Toyota 4Runner. Pulse durations of 0.2 and 0.3 seconds were evaluated. The pulse magnitude was a nominal 80 degrees. Testing was conducted for both left and right steering directions and at 40 and 50 mph. Four tests were conducted for each condition. The data were then processed and vehicle response to handwheel input transfer functions were generated using frequency domain techniques.

A comparison of the mean value magnitude and phase angle transfer function data generated for the 40 mph, 0.2 second pulse duration, and left and right steering directions are given in Figures 10.16 to 10.19. The corrected lateral acceleration to handwheel frequency response is given first, followed by similar data for roll angle, roll rate, and yaw rate. The right steer pulse generally produced a greater magnitude at the lower end of the frequency range for all four of the evaluated vehicle responses. Other than this general trend, the shape of the magnitude and phase angle curves are very similar for each direction.

A comparison of the mean value magnitude and phase angle transfer function data generated for the 40 mph, left steer direction, and 0.2 and 0.3 second pulse duration are given in Figures 10.20 to 10.23. The curves are very similar for these two conditions. This suggests that either pulse duration would be appropriate for evaluating the vehicle for the frequency range of interest. The most disparate curve is for the magnitude portion for roll rate (Figure 10.22). The roll rate resonance peak for the 0.3 second pulse is less than that for the 0.2 second pulse.

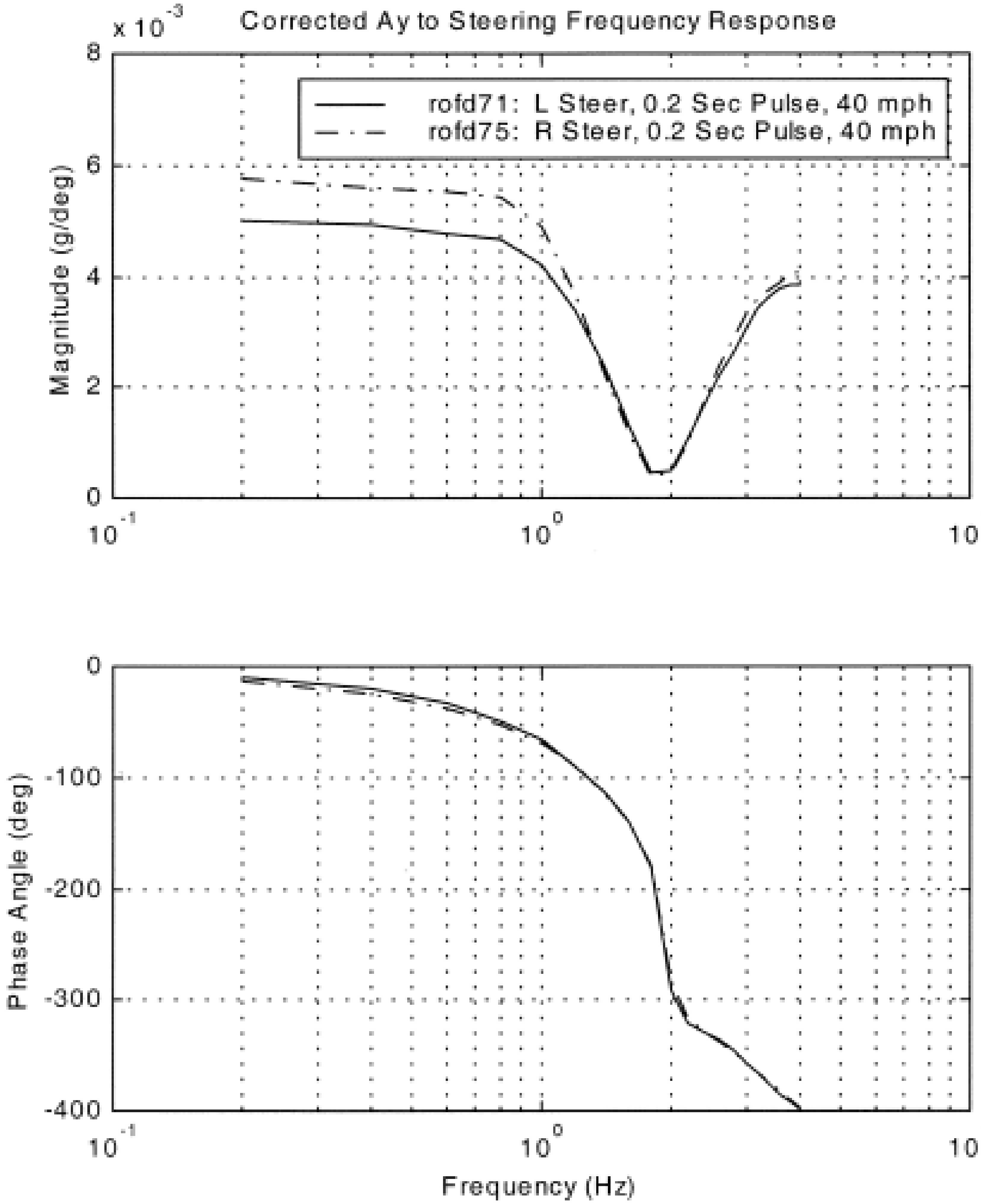


Figure 10.16 -- Comparison of Left and Right Steer, 0.2 Second Pulse Duration, and 40 mph Frequency Response Curves - Corrected Lateral Acceleration

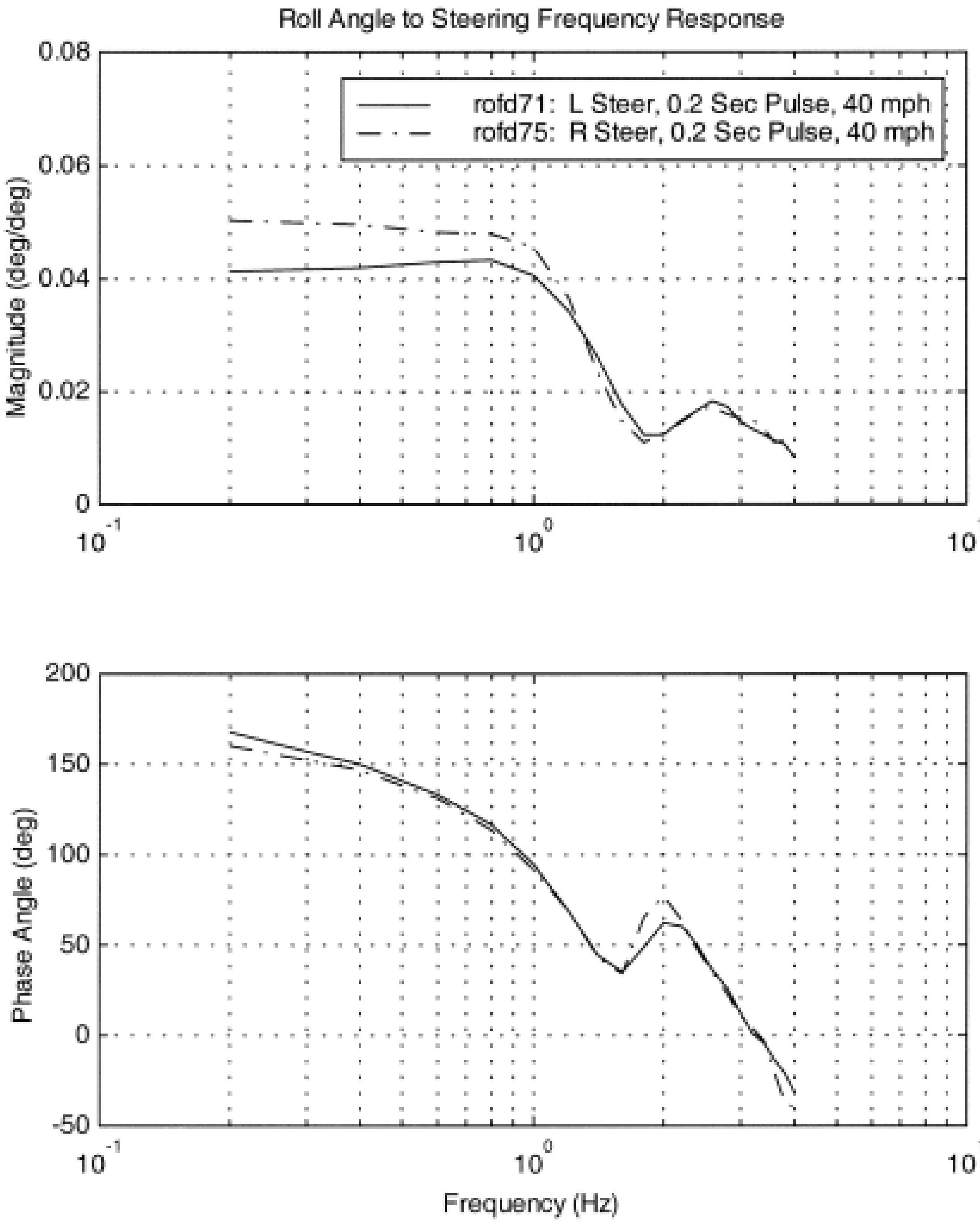


Figure 10.17 -- Comparison of Left and Right Steer, 0.2 Second Pulse Duration, and 40 mph Frequency Response Curves - Roll Angle

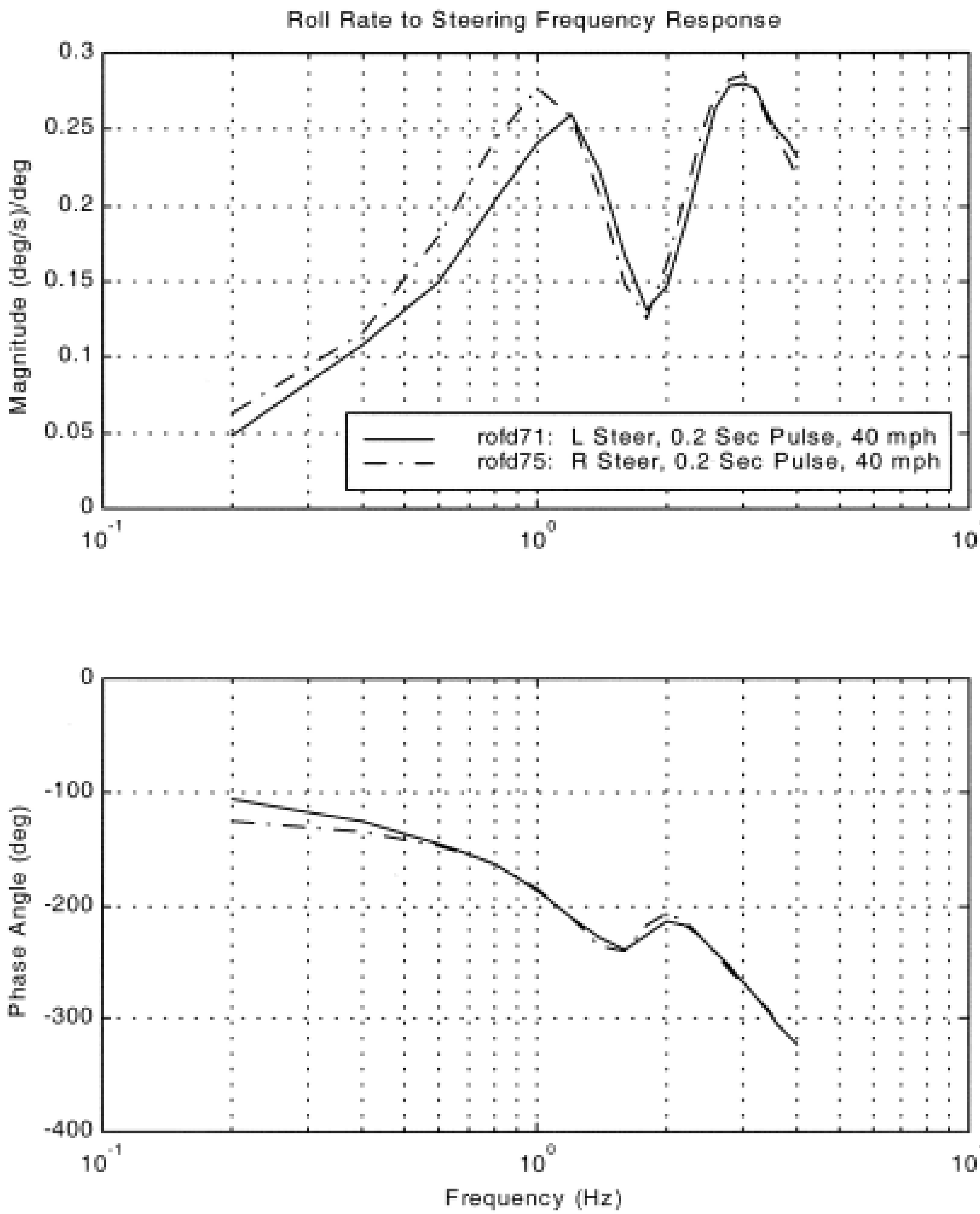


Figure 10.18 -- Comparison of Left and Right Steer, 0.2 Second Pulse Duration, and 40 mph Frequency Response Curves - Roll Rate

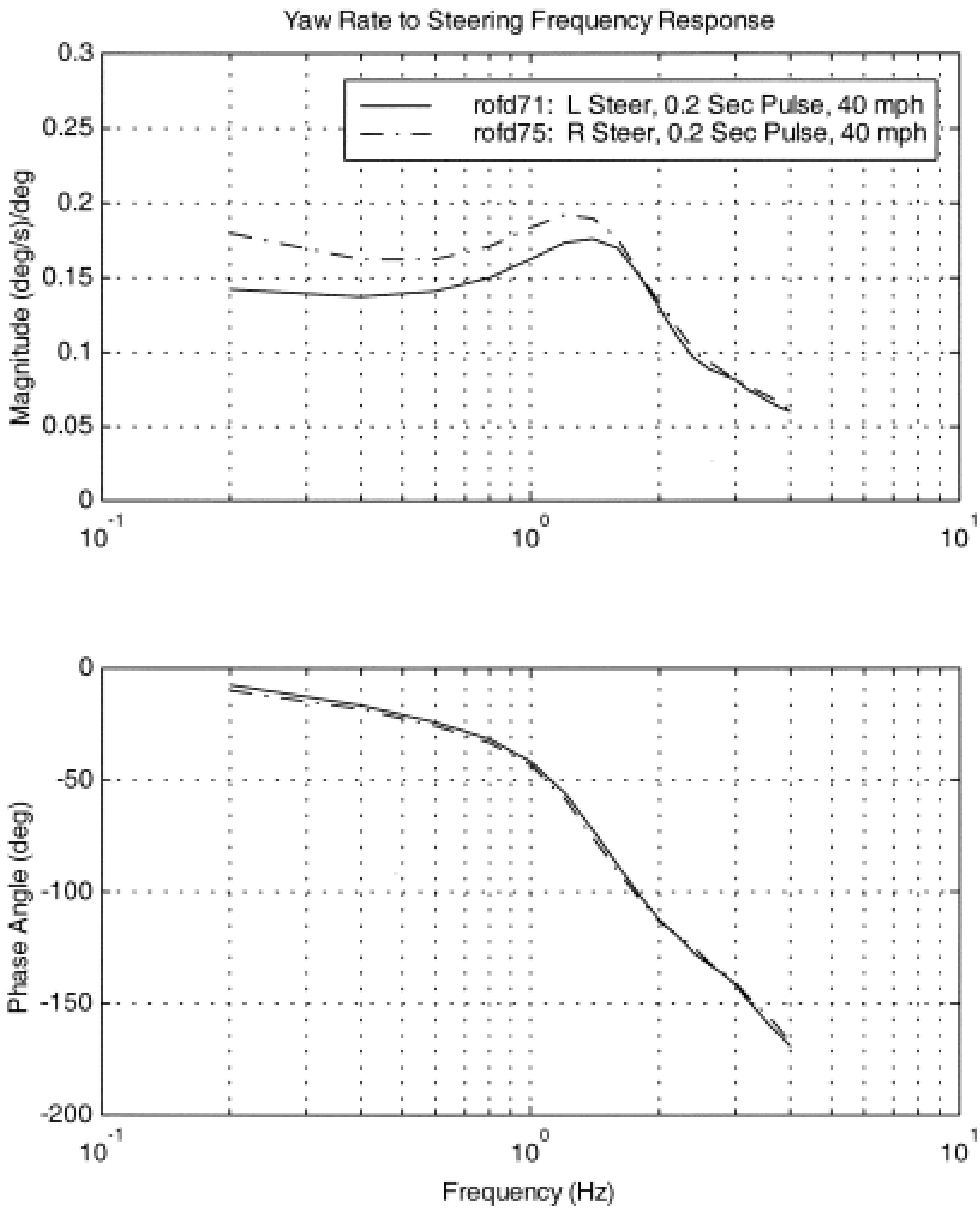


Figure 10.19 -- Comparison of Left and Right Steer, 0.2 Second Pulse Duration, and 40 mph Frequency Response Curves - Yaw Rate

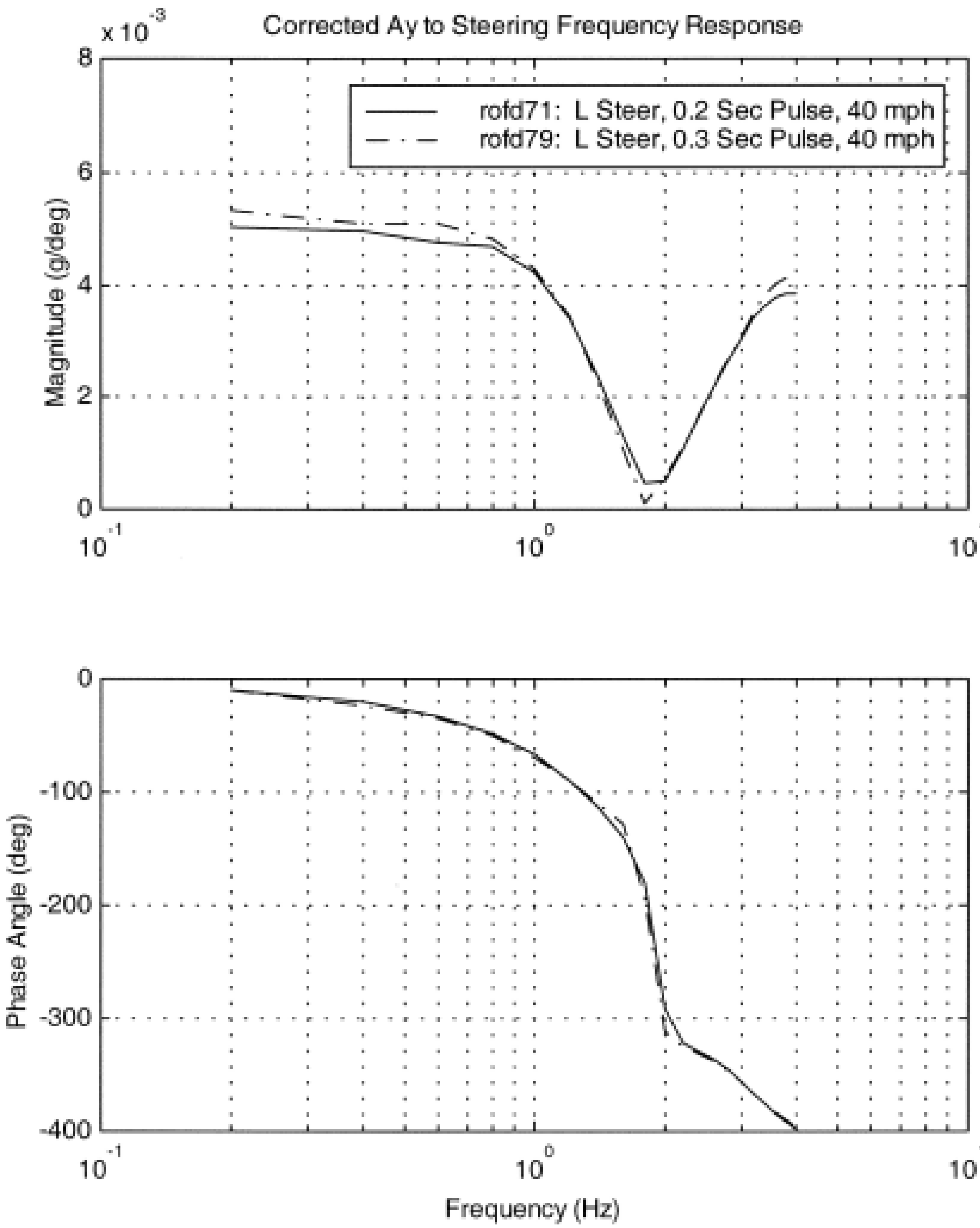


Figure 10.20 -- Comparison of Left Steer, 0.2 and 0.3 Second Pulse Duration, and 40 mph Frequency Response Curves - Corrected Lateral Acceleration

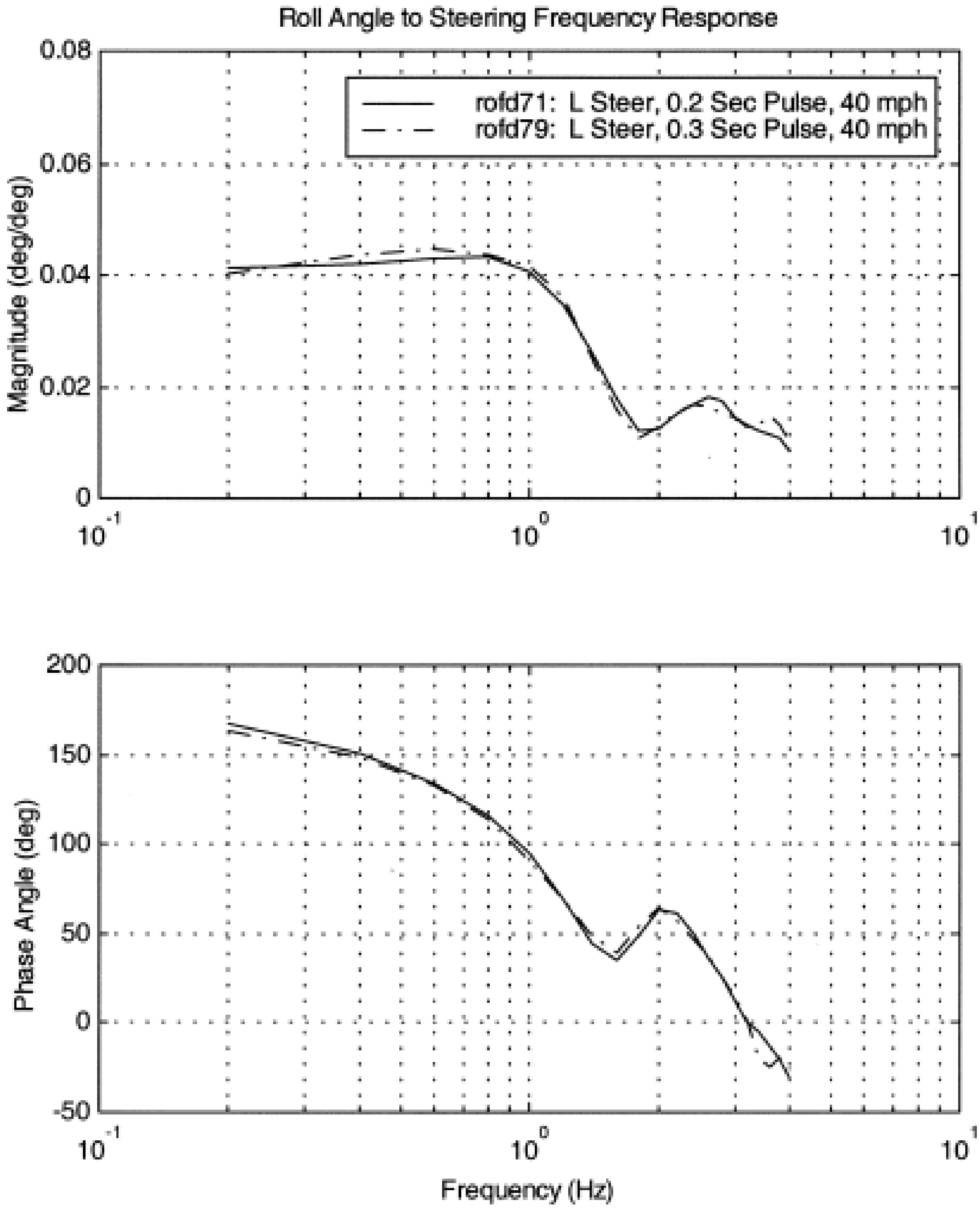


Figure 10.21 -- Comparison of Left Steer, 0.2 and 0.3 Second Pulse Duration, and 40 mph Frequency Response Curves - Roll Angle

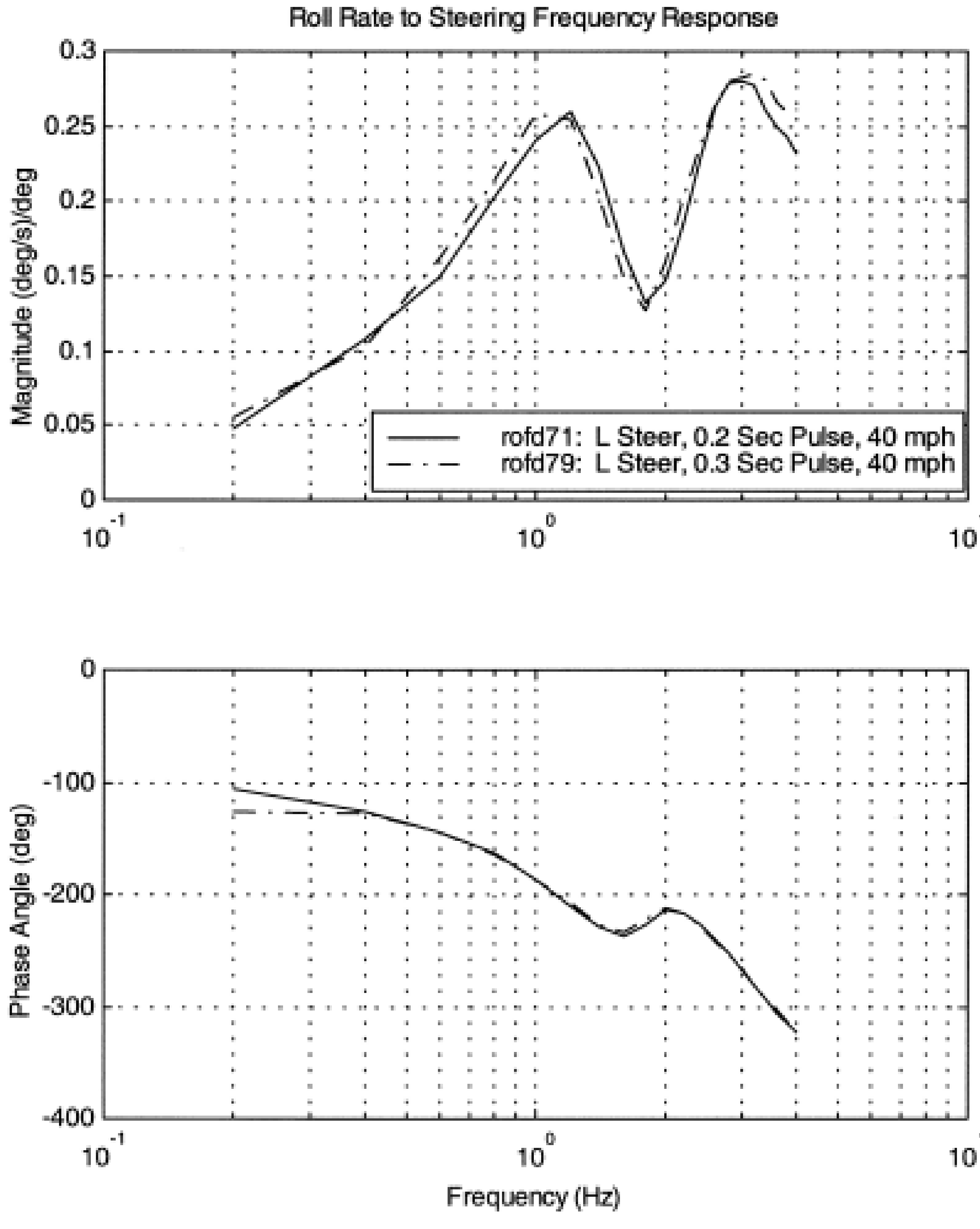


Figure 10.22 -- Comparison of Left Steer, 0.2 and 0.3 Second Pulse Duration, and 40 mph Frequency Response Curves - Roll Rate

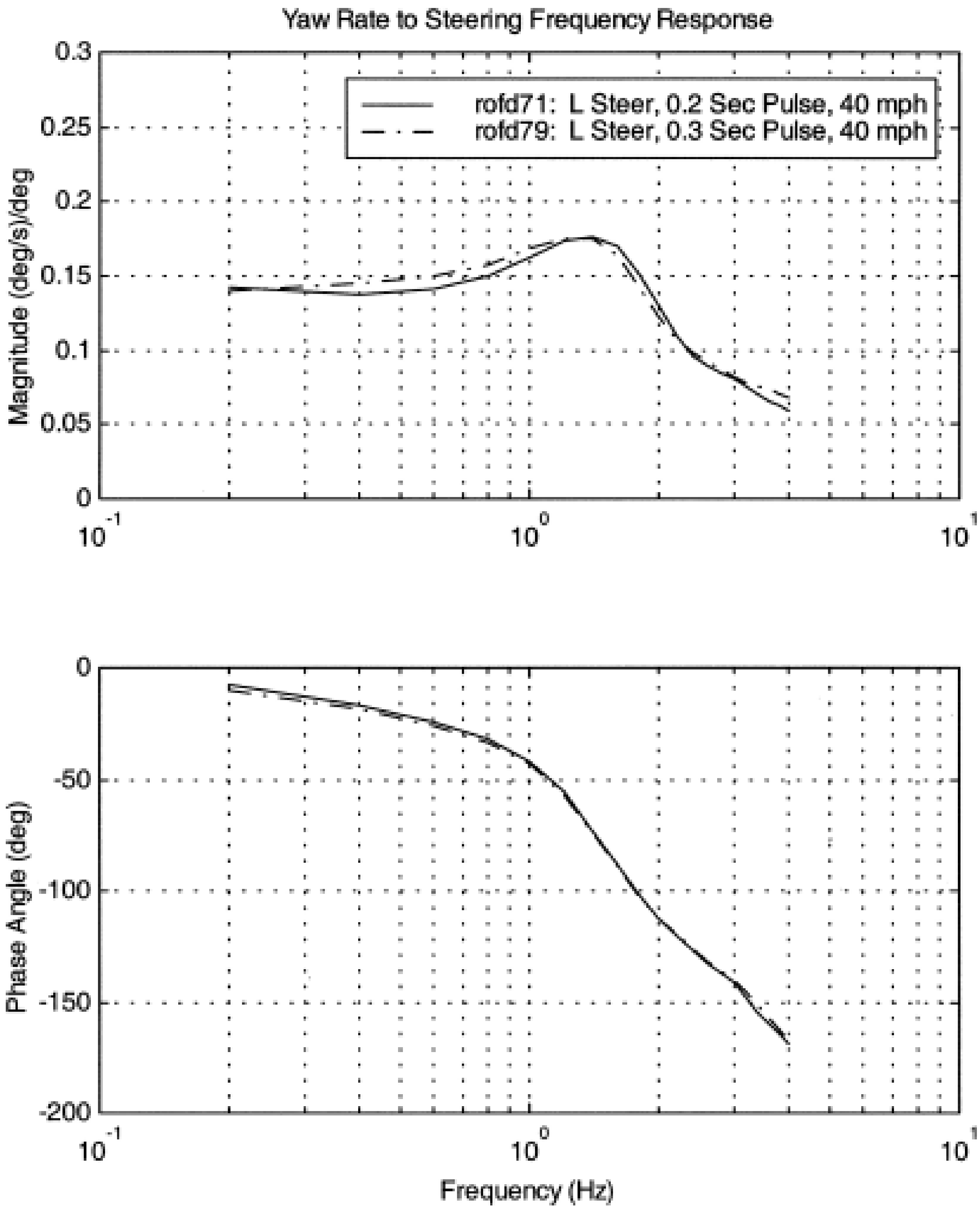


Figure 10.23 -- Comparison of Left Steer, 0.2 and 0.3 Second Pulse Duration, and 40 mph Frequency Response Curves - Yaw Rate

A comparison of 40 and 50 mph tests is given in Figures 10.24 through 10.27. The data compared are for the 0.2 second pulse duration and left steer direction. As would be expected, the magnitude portion of the curves are generally greater for the 50 mph tests. This is especially true at the lower end of the frequency spectrum (<1.5 Hz). The phase angle response curves are very similar for both conditions. The 50 mph roll rate resonance peak has a much higher magnitude than that for the 40 mph test condition (Figure 10.26). There does not appear to be a shift in the resonance frequency though. The yaw rate resonance peak is also higher for the 50 mph condition and does show a slight shift in frequency (1.6 versus 1.3 Hz). The other 40 and 50 mph conditions (left and right steer and 0.2 and 0.3 second pulse duration) produced similar results.

10.3.2 Sinusoidal Sweep Test Results

Sinusoidal sweep tests were performed with the 1990 Toyota 4Runner. Two sweep ranges and two vehicle speeds were evaluated. The two sweep ranges were 0.1 to 1.0 Hz and 0.1 to 2.5 Hz. The two vehicle speeds were 40 and 50 mph which were the same as those used in the pulse steer tests.

The 40 mph frequency response results for the two frequency ranges are given in Figures 10.28 to 10.31. As would be expected given the frequency ranges tested, the two sets of curves are very similar up to 0.9 Hz and are quite disparate beyond 0.9 Hz. Although not shown in these figures, the coherence drops off dramatically above the range of handwheel input frequency.

The 0.1 to 2.5 Hz, 40 mph frequency response data is plotted along with the left and right 0.2 second pulse, 40 mph data in Figures 10.32 to 10.35. At the lower end of the frequency range, the magnitude portion of the response falls between the left and right pulse steer data. At the higher frequency ranges, all three curves are very similar. The roll rate and yaw rate magnitudes for the sine sweep tests takes a slight dip in the 1.0 to 1.3 Hz range. This dip did not occur in the pulse steer tests. It is not clear why this dip occurred. The coherence is nearly 1.0 over the entire frequency range plotted. Other than these slight dips in response, the pulse steer and sine sweep tests appear to produce very similar results.

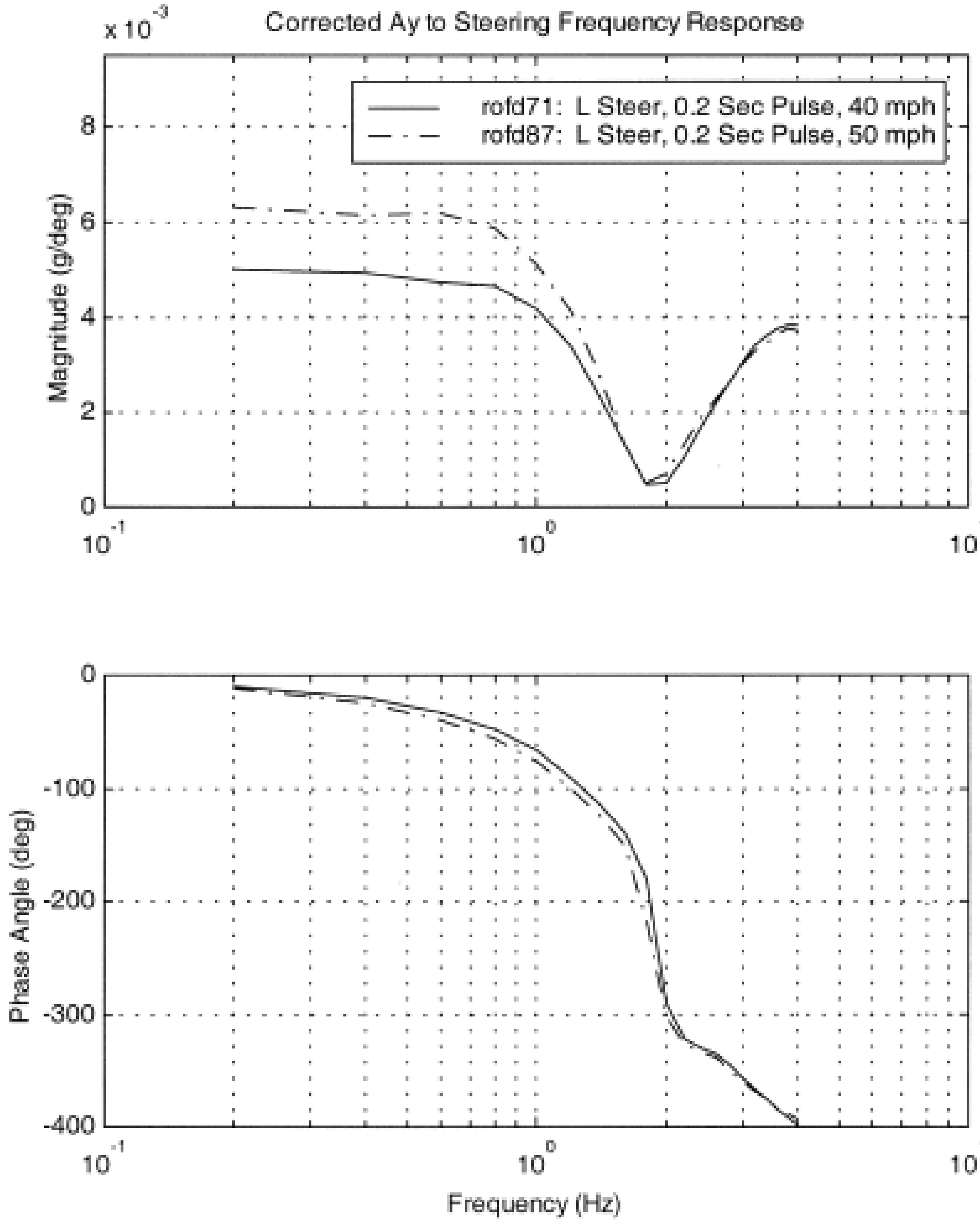


Figure 10.24 -- Comparison of Left Steer, 0.2 Second Pulse Duration, and 40 and 50 mph Frequency Response Curves - Corrected Lateral Acceleration

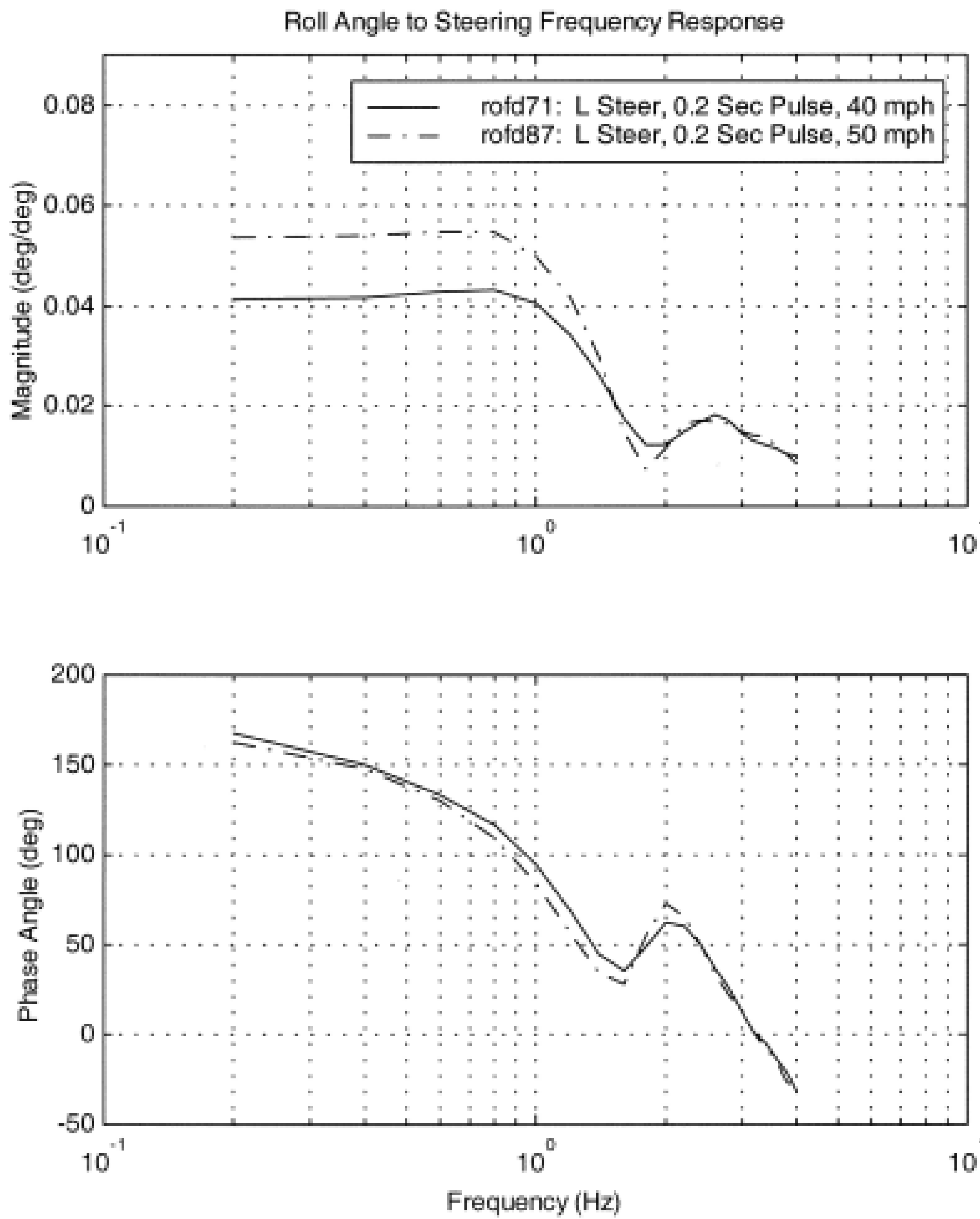


Figure 10.25 -- Comparison of Left Steer, 0.2 Second Pulse Duration, and 40 and 50 mph Frequency Response Curves - Roll Angle

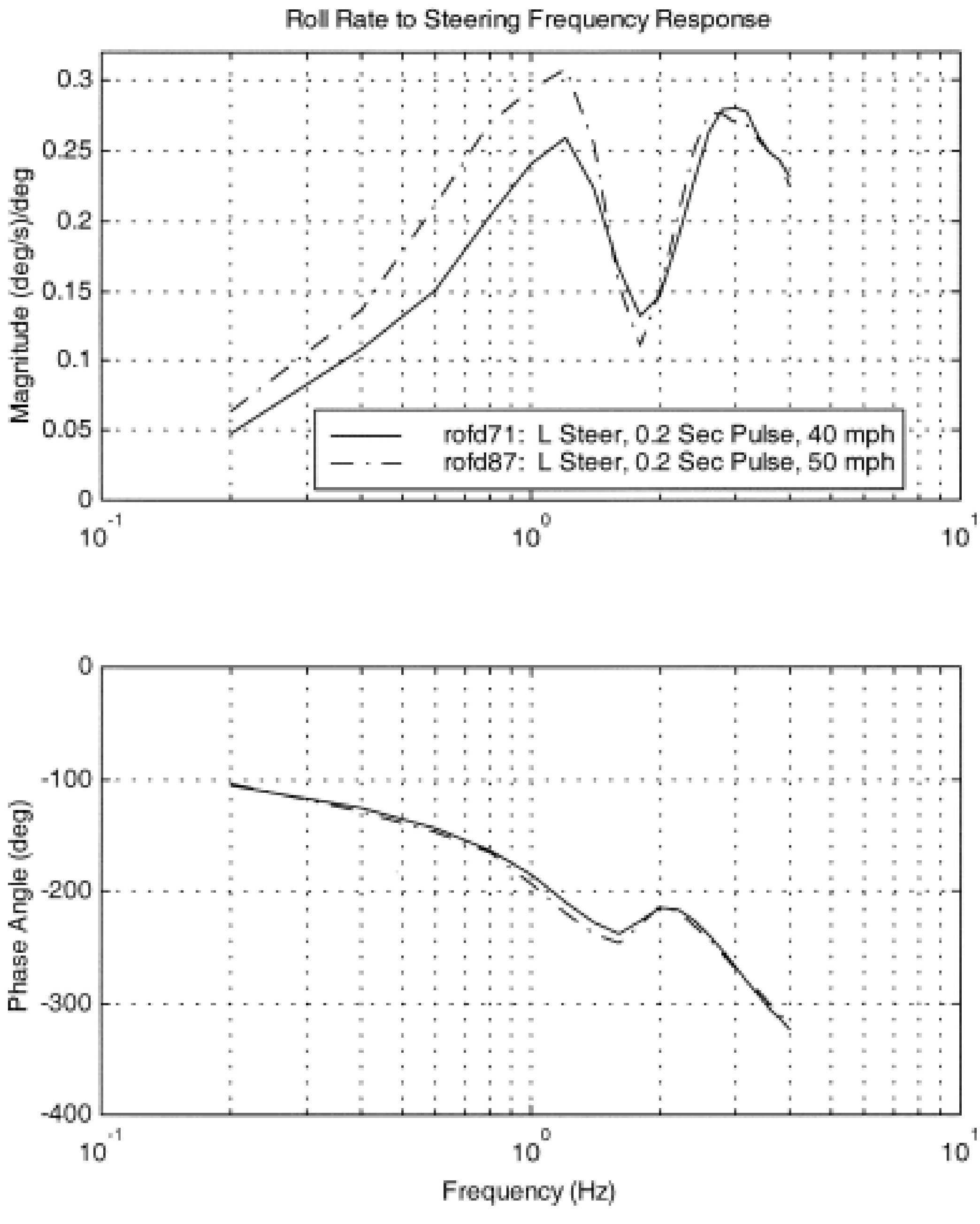


Figure 10.26 -- Comparison of Left Steer, 0.2 Second Pulse Duration, and 40 and 50 mph Frequency Response Curves - Roll Rate

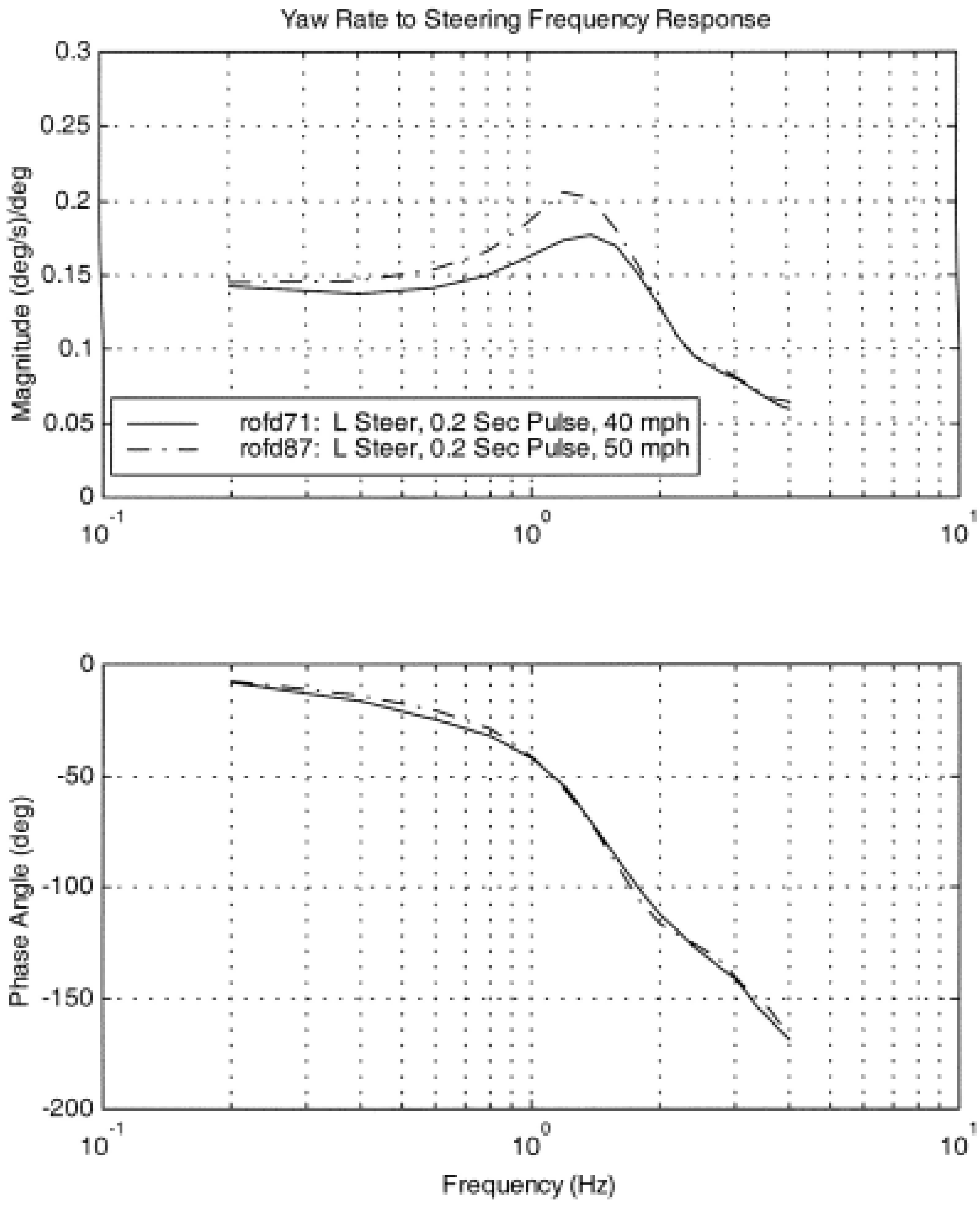


Figure 10.27 -- Comparison of Left Steer, 0.2 Second Pulse Duration, and 40 and 50 mph Frequency Response Curves -Yaw Rate

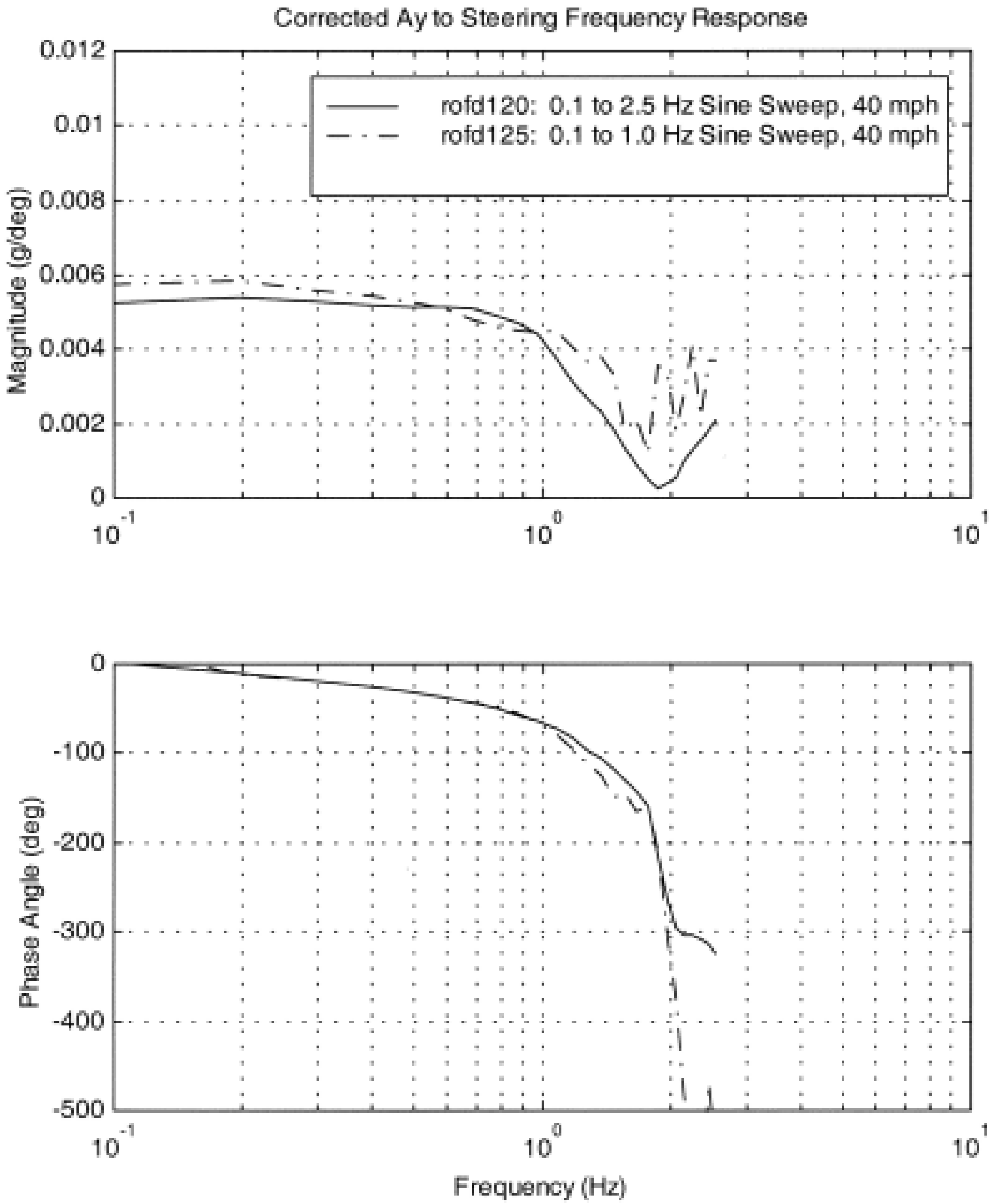


Figure 10.28 -- Comparison of 40 mph, 0.1 to 1.0 and 0.1 to 2.5 Hertz Sinusoidal Sweep Frequency Response Curves - Corrected Lateral Acceleration

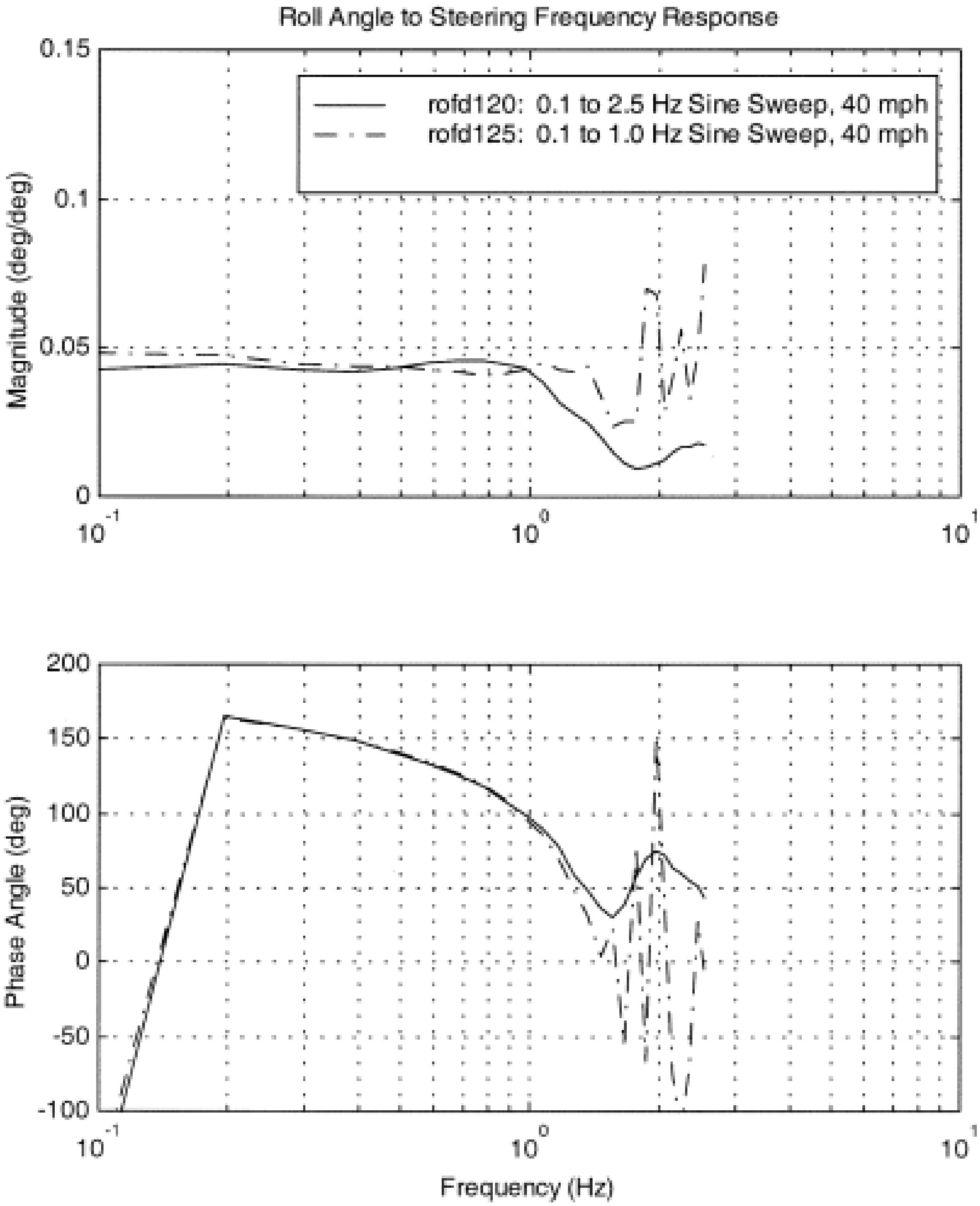


Figure 10.29 -- Comparison of 40 mph, 0.1 to 1.0 and 0.1 to 2.5 Hertz Sinusoidal Sweep Frequency Response Curves - Roll Angle

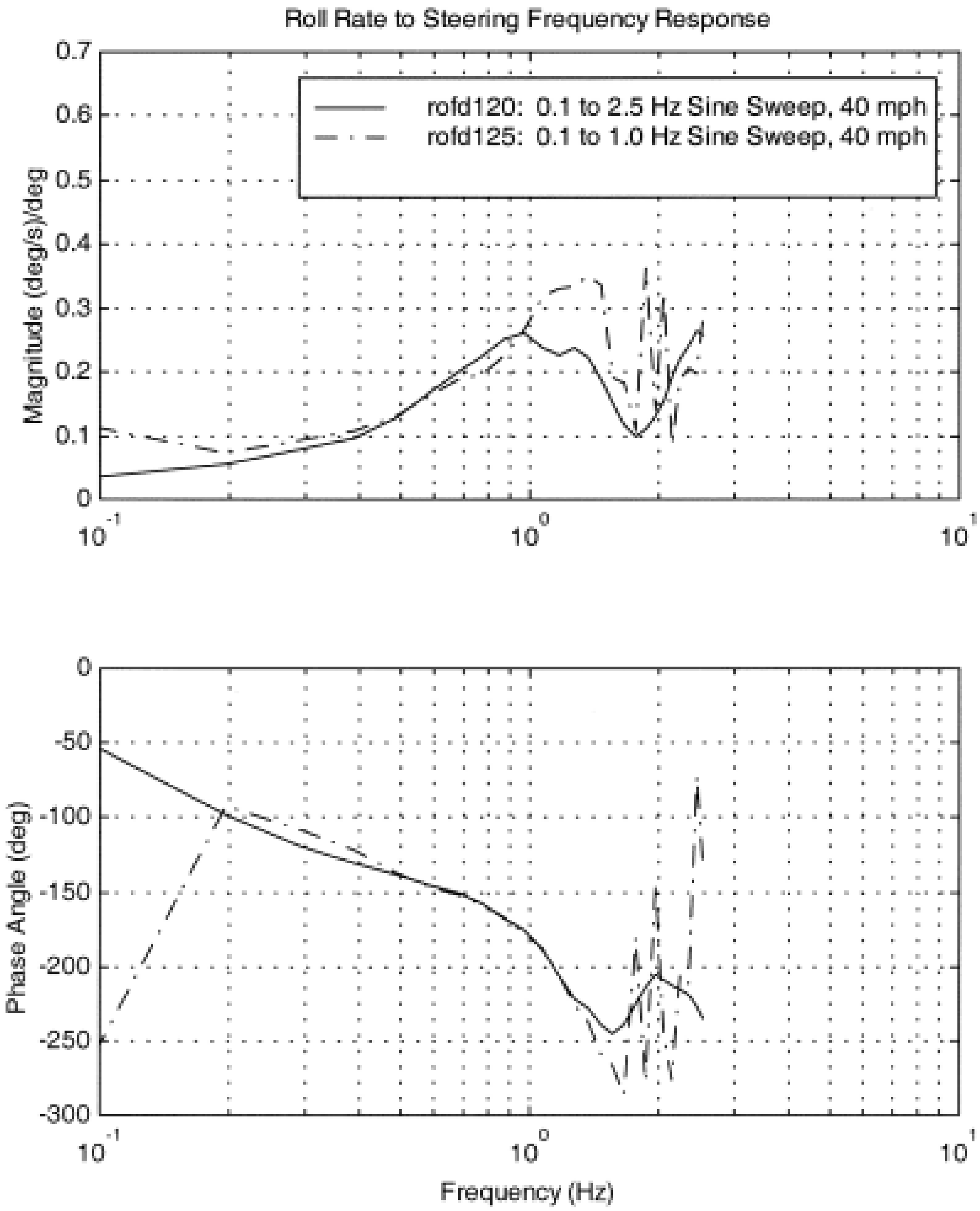


Figure 10.30 -- Comparison of 40 mph, 0.1 to 1.0 and 0.1 to 2.5 Hertz Sinusoidal Sweep Frequency Response Curves - Roll Rate

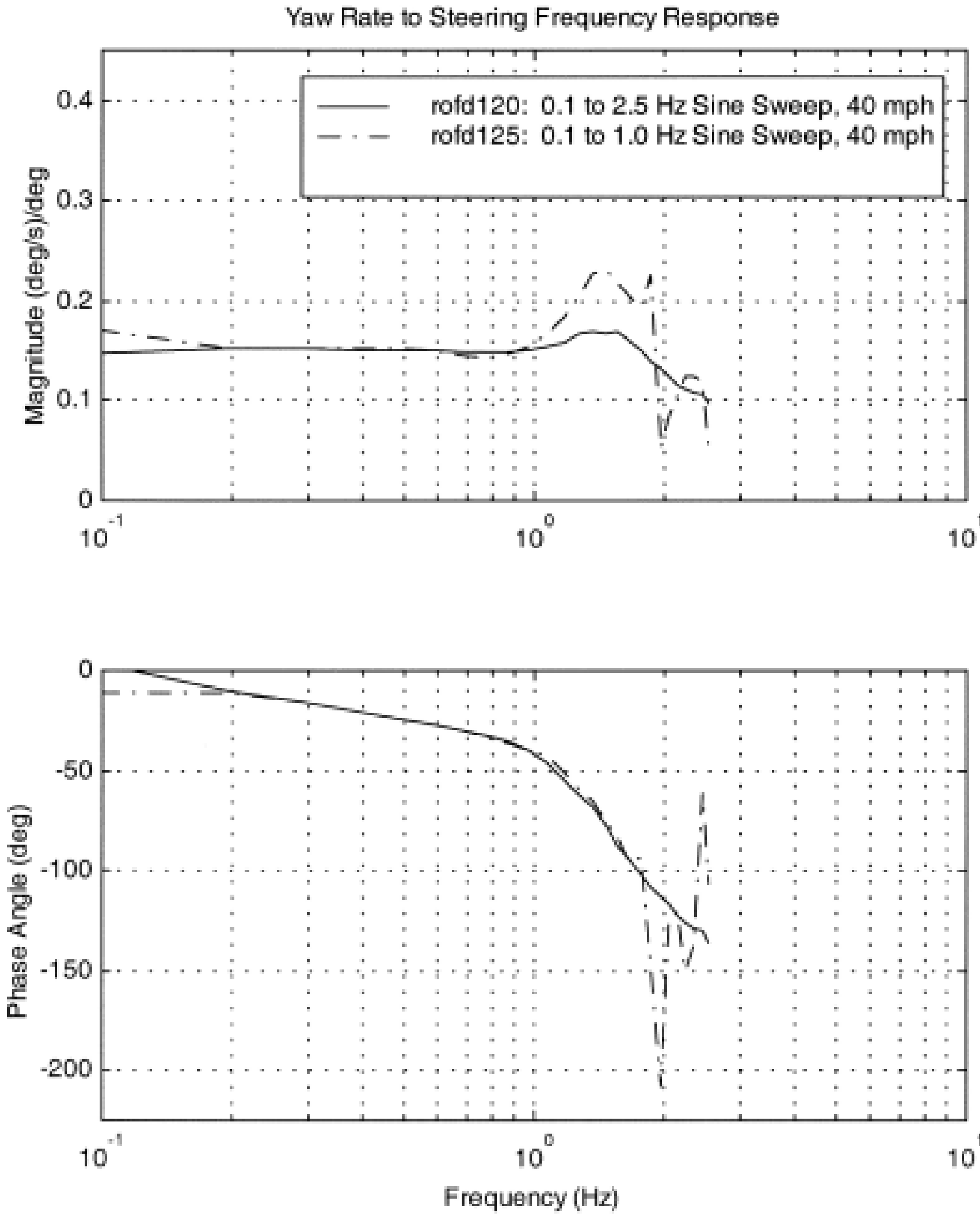


Figure 10.31 -- Comparison of 40 mph, 0.1 to 1.0 and 0.1 to 2.5 Hertz Sinusoidal Sweep Frequency Response Curves - Yaw Rate

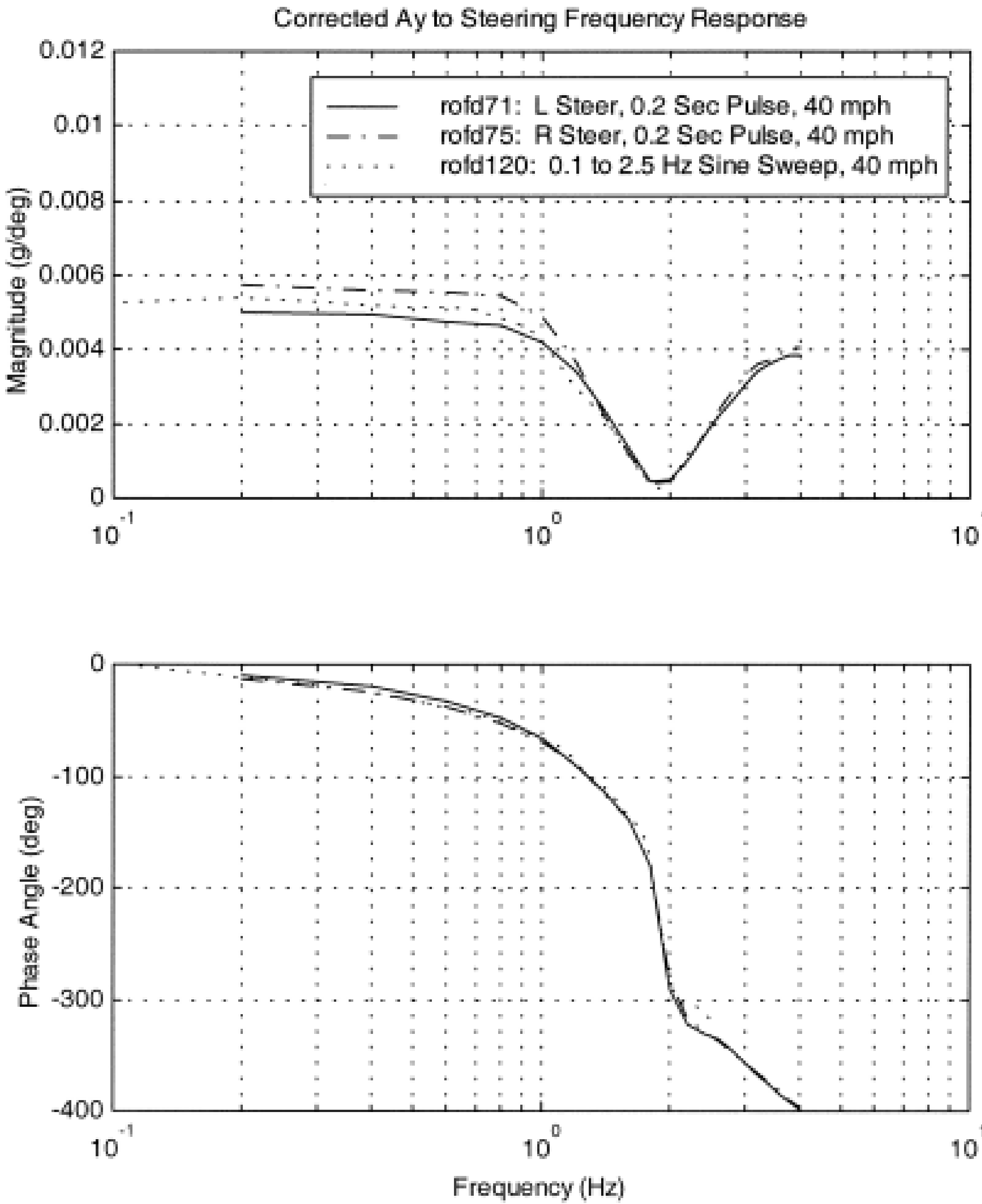


Figure 10.32 -- Comparison of 0.2 Second Pulse Duration and Sinusoidal Sweep Frequency Response Curves - Corrected Lateral Acceleration

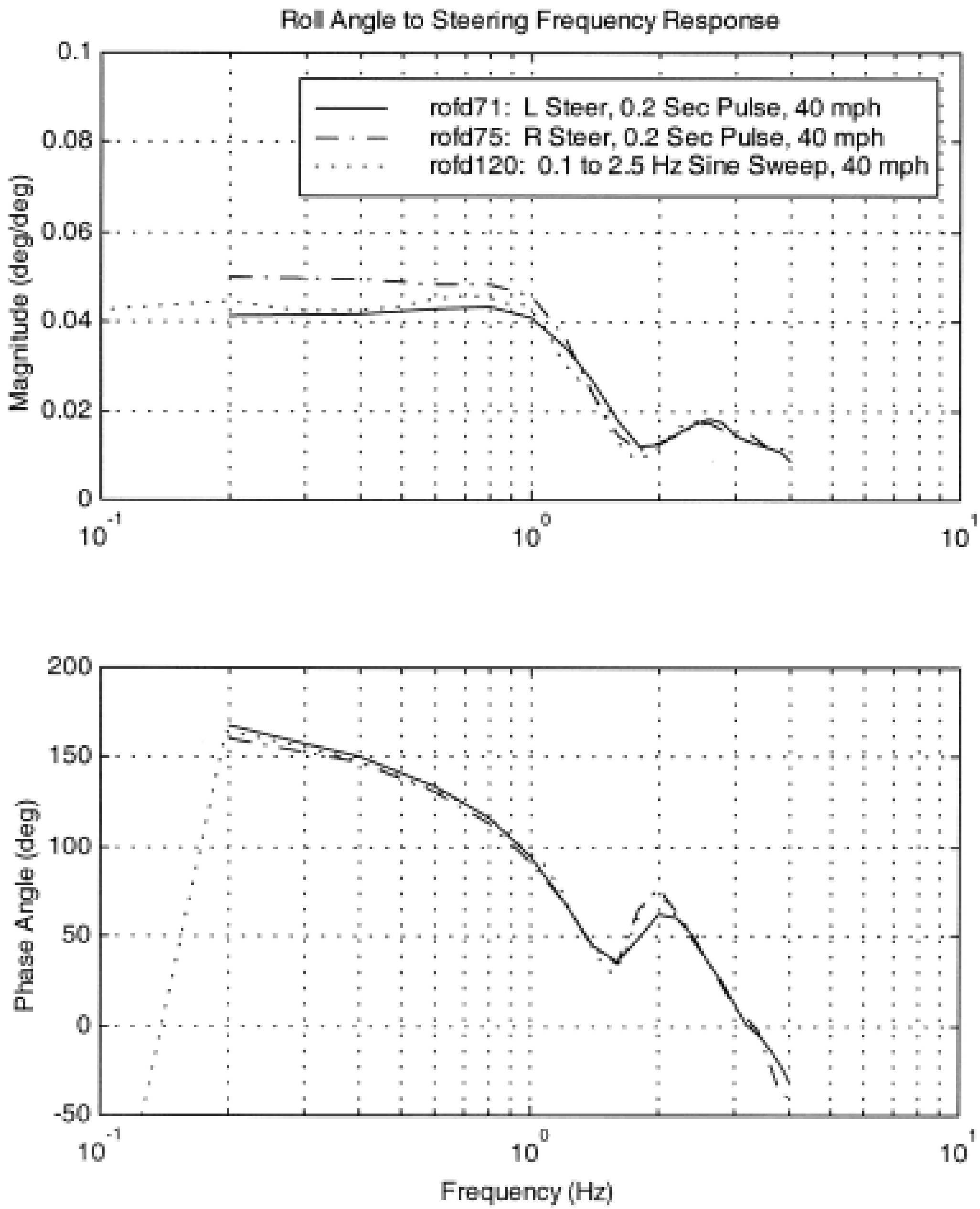


Figure 10.33 -- Comparison of 0.2 Second Pulse Duration and Sinusoidal Sweep Frequency Response Curves - Roll Angle

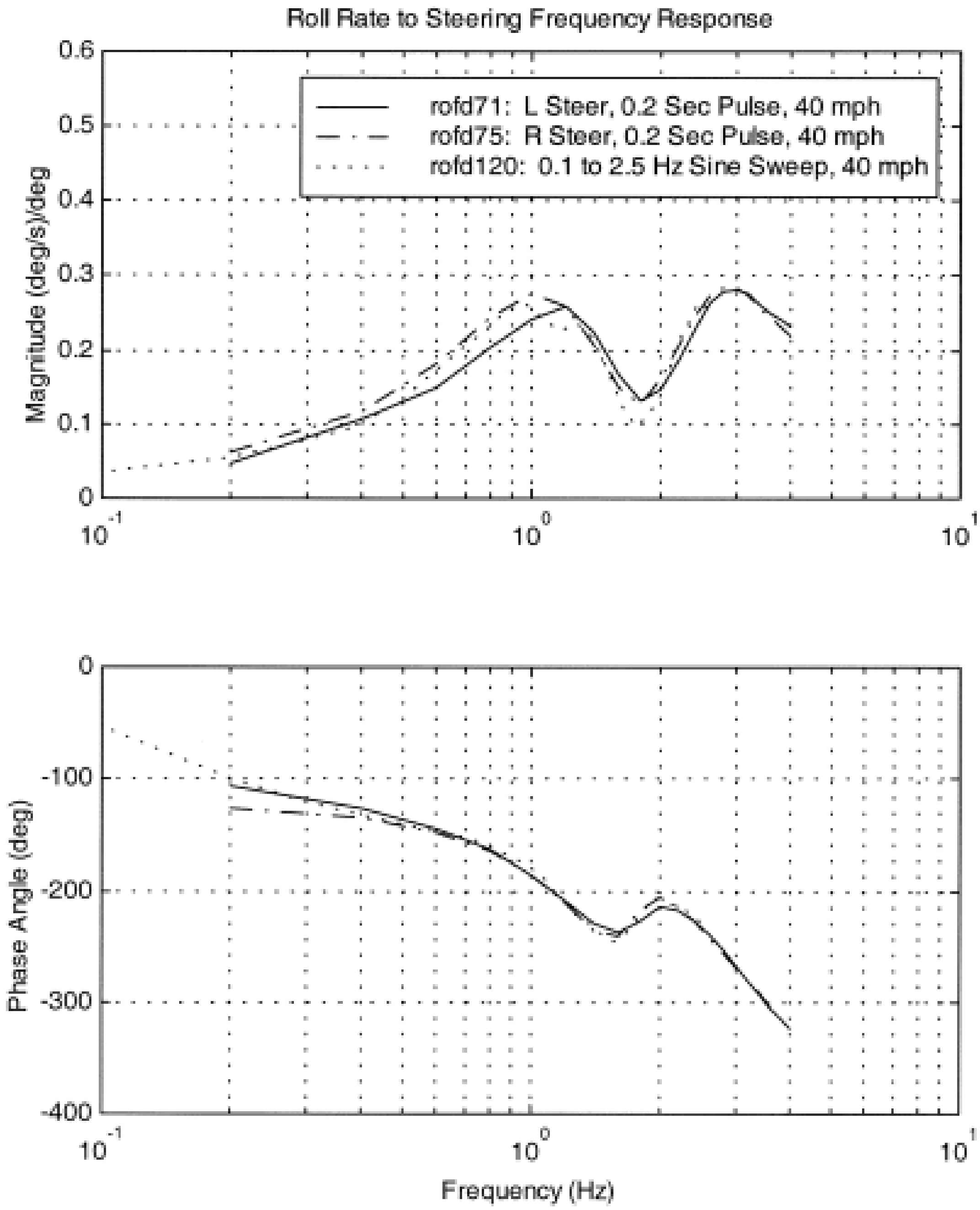


Figure 10.34 -- Comparison of 0.2 Second Pulse Duration and Sinusoidal Sweep Frequency Response Curves - Roll Rate

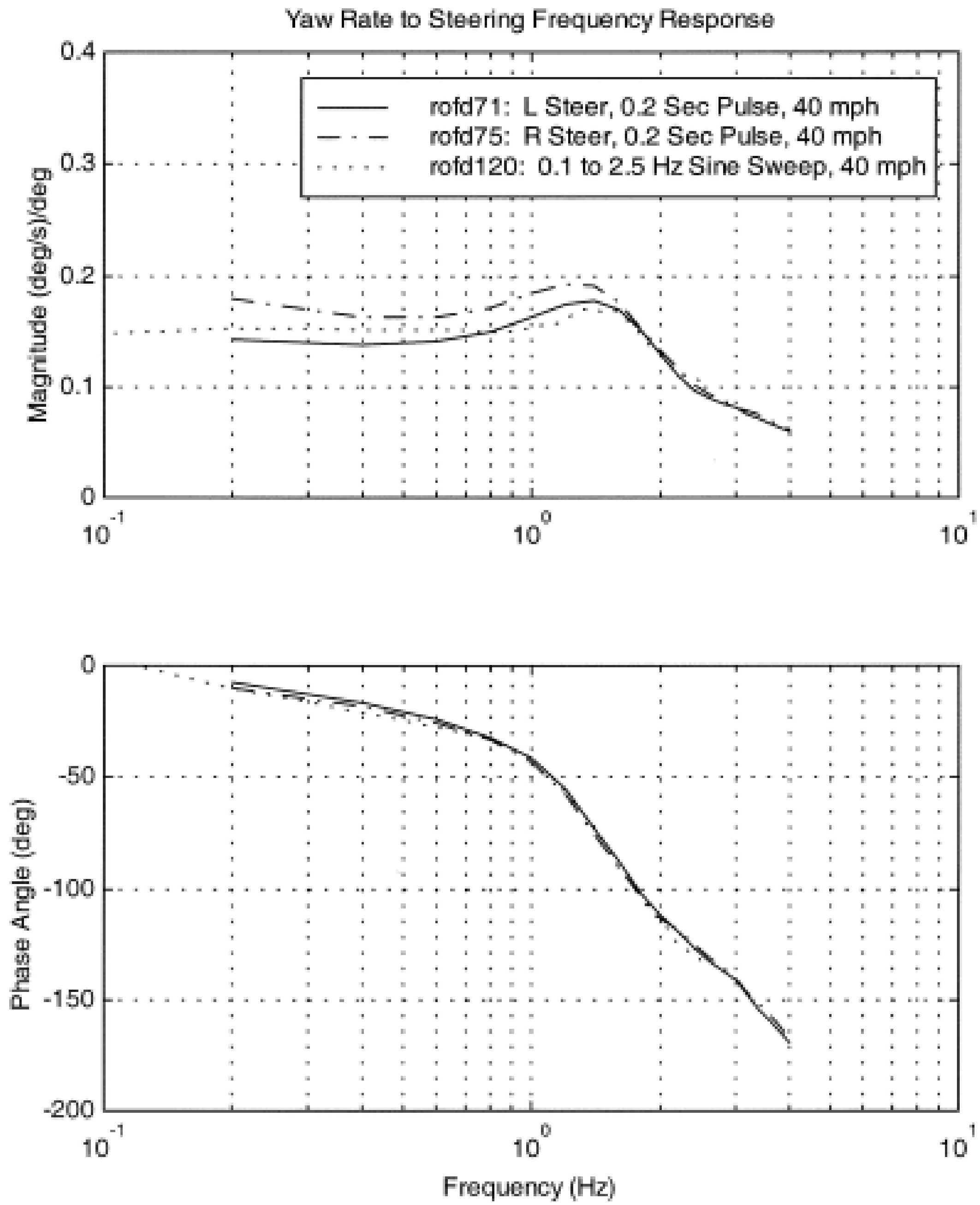


Figure 10.35 -- Comparison of 0.2 Second Pulse Duration and Sinusoidal Sweep Frequency Response Curves - Yaw Rate

10.3.3 Resonance Steer Type Inputs for Determining Roll Natural Frequency

As can be seen in all of the previously discussed roll angle response plots, the roll angle to steering frequency response did not have a strong resonance peak and was relatively flat over a wide frequency range (0.1 to 1.0 Hz). The resonance test consists of applying multiple cycles of a sinusoidal input at a pre-determined natural frequency. Since a natural frequency could not be determined for roll angle due to its relatively flat response, a series of resonance type tests were performed at 0.6, 0.7, 0.8, 0.9, and 1.0 Hz to see if a more definite peak could be determined. These tests were performed at 40 and 50 mph. The steering magnitudes for the 40 mph tests were nominally 80, 100, and 120 degrees. The 50 mph tests were performed with 60, 80, 90, and 100 degrees of steering.

The handwheel input for a resonance test is shown in Figure 10.36. A typical set of vehicle responses to this type of input are shown in Figures 10.37 to 10.40.

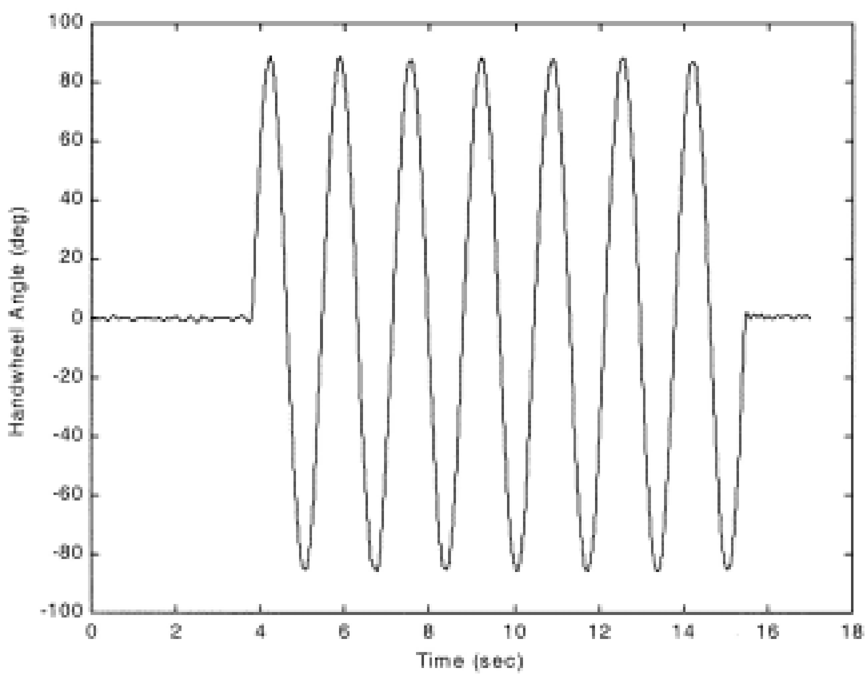


Figure 10.36 -- Handwheel Angle as a Function of Time for a Nominal Resonance Steer Test

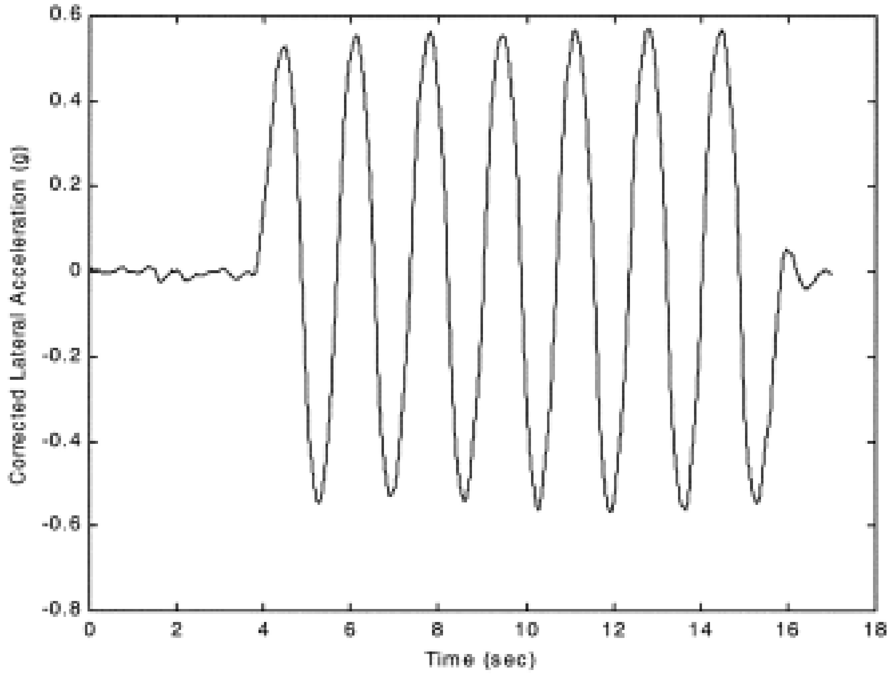


Figure 10.37 -- Corrected Lateral Acceleration as a Function of Time for a Nominal Resonance Steer Test

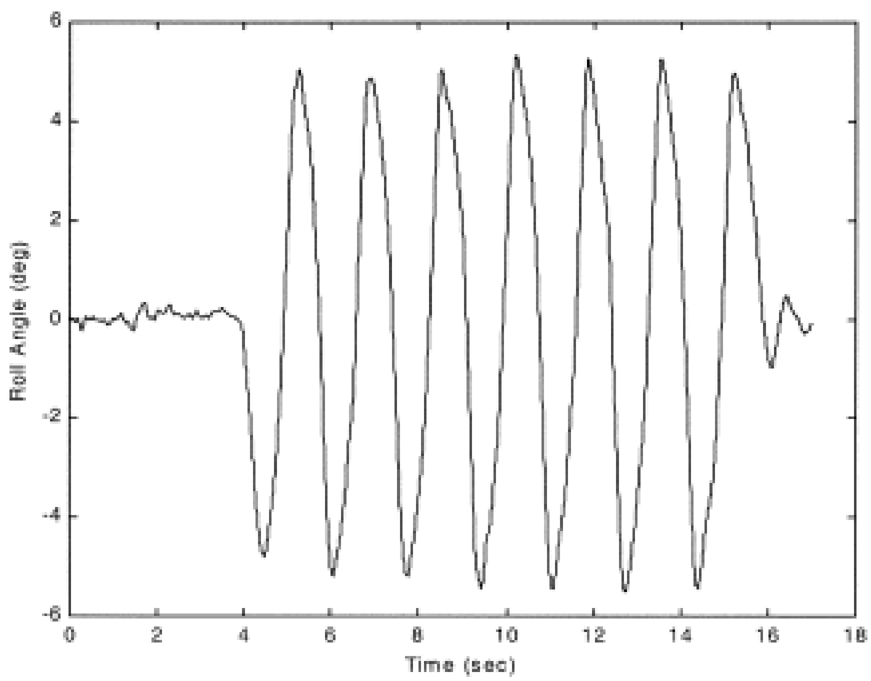


Figure 10.38 -- Roll Angle as a Function of Time for a Nominal Resonance Steer Test

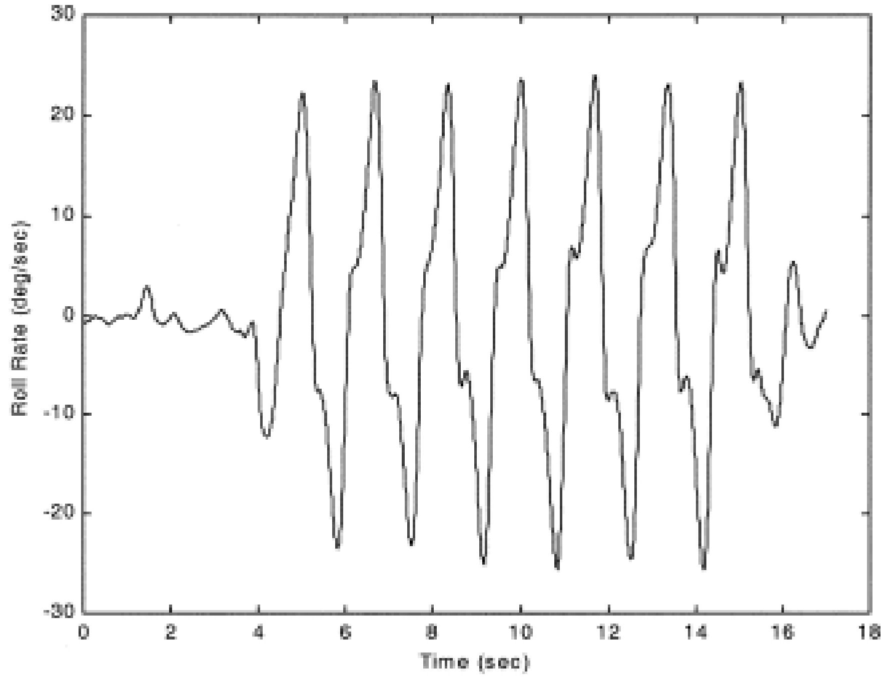


Figure 10.39 -- Roll Rate as a Function of Time for a Nominal Resonance Steer Test

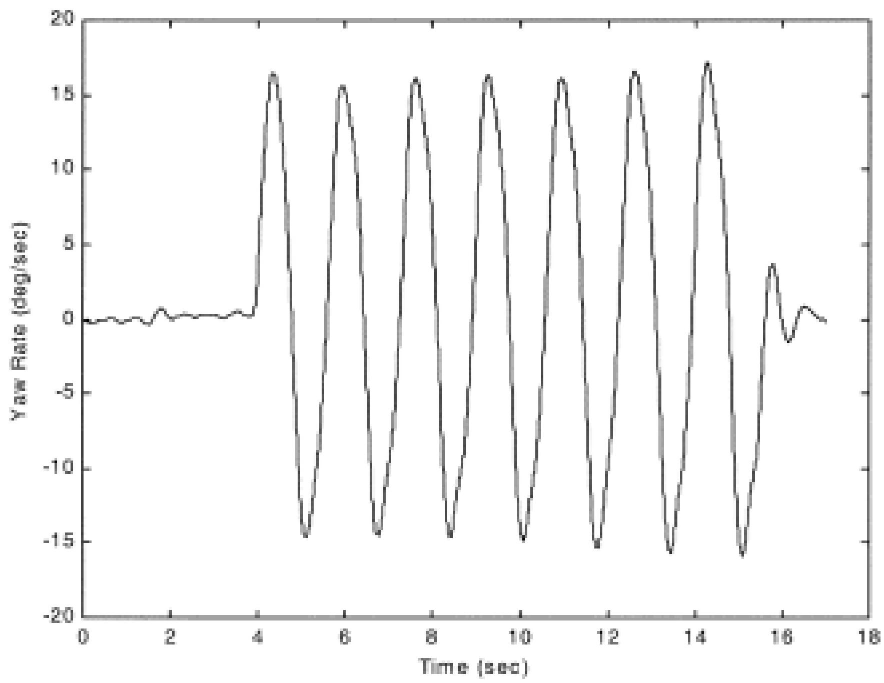


Figure 10.40 -- Yaw Rate as a Function of Time for a Nominal Resonance Steer Test

For analysis purposes, the minimum and maximum vehicle responses for each cycle of steering input were averaged. These average values were then divided by the magnitude of the steering input. This resulted in a determination of the magnitude portion of the frequency response of the vehicle.

The 40 mph results are plotted in Figures 10.41 to 10.44. Results from the pulse steer and sinusoidal sweep tests showed that the magnitude of the corrected lateral acceleration to steering frequency was approximately 0.005 g/deg for lower frequencies and then started to roll down at approximately 0.8 Hertz. This was also found to be the case for "resonance" steer profiles (Figure 10.41). The 100 and 120 degree steering inputs produced results that were slightly lower than that found at 80 degrees. This suggests that an increase in the steering magnitude does not necessarily produce a corresponding similar increase in the corrected lateral acceleration. No repeat testing was performed and so these results are not definitive. Repeat testing would have to be performed to determine the variability in making these types of measurements. Only then could more definitive statements be made.

The roll angle frequency response is given in Figure 10.42. As was the case for the other methods (pulse steer and sinusoidal sweep), the frequency response was very flat at approximately 0.05 deg/deg on the lower end of the frequency spectrum and then starts to roll down at approximately 0.8 to 0.9 Hertz. As was the case for corrected lateral acceleration, the 100 and 120 degree steering inputs produced a slightly lower results than those found at 80 degrees. It was hoped that this method may produce a more definite high point in the lower end of the frequency spectrum, but this was not found to be the case.

The roll rate frequency response is given in Figure 10.43. The pulse steer and sinusoidal sweep methods produced results that started in the 0.15 to 0.18 deg/sec/deg range at 0.6 Hertz and increased to 0.24 to 0.28 at 1 Hertz. The resonance steer inputs produced similarly increasing response for this frequency range. The 120 degree steering input did produce a more flat response compared to the 80 and 100 degree steering inputs.

The yaw rate frequency response found using the resonant steering profile input had the same slightly increasing magnitude over the 0.6 to 1.0 Hertz range that was found using the pulse steer and sinusoidal sweep steering profiles (Figure 10.44). For yaw rate, the 100 and 120 degree steering profiles produced slightly higher results than those found at 80 degrees.

Similar analysis of the 50 mph data shows that the resonant steering profiles produces similar results to those found using the pulse steer and sinusoidal sweep steering profiles.

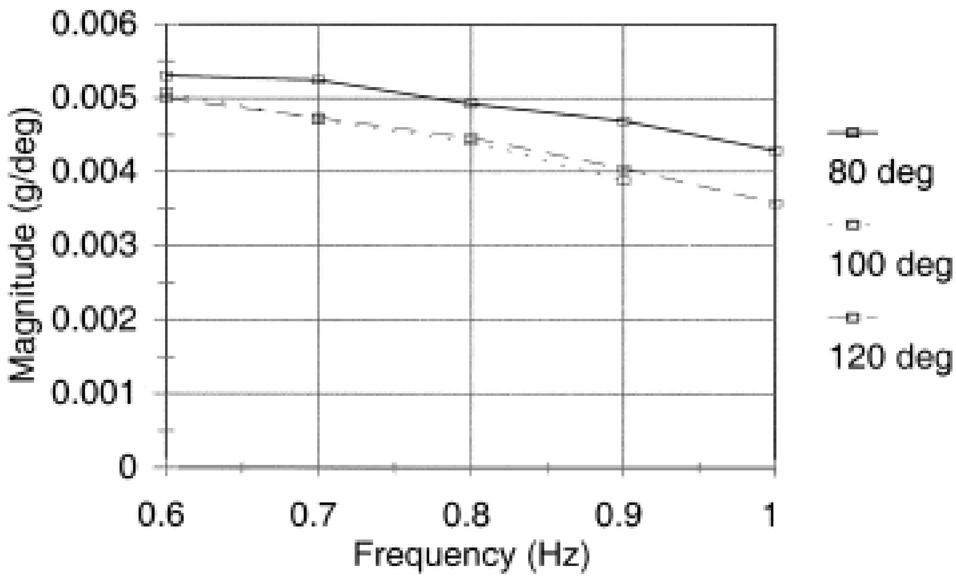


Figure 10.41 -- Corrected Lateral Acceleration Frequency Response Using "Resonance" Steering Profile - 40 mph

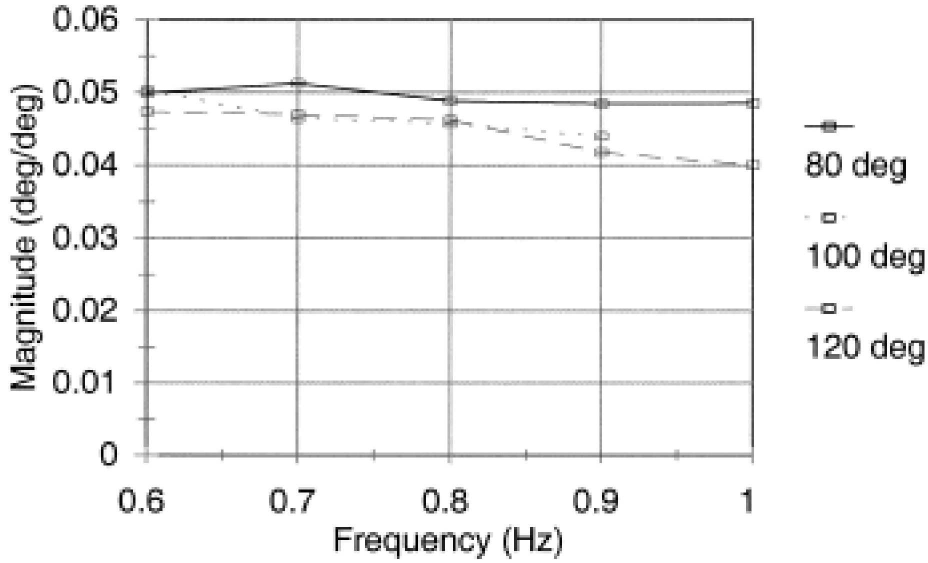


Figure 10.42 -- Roll Angle Frequency Response Using "Resonance" Steering Profile - 40 mph

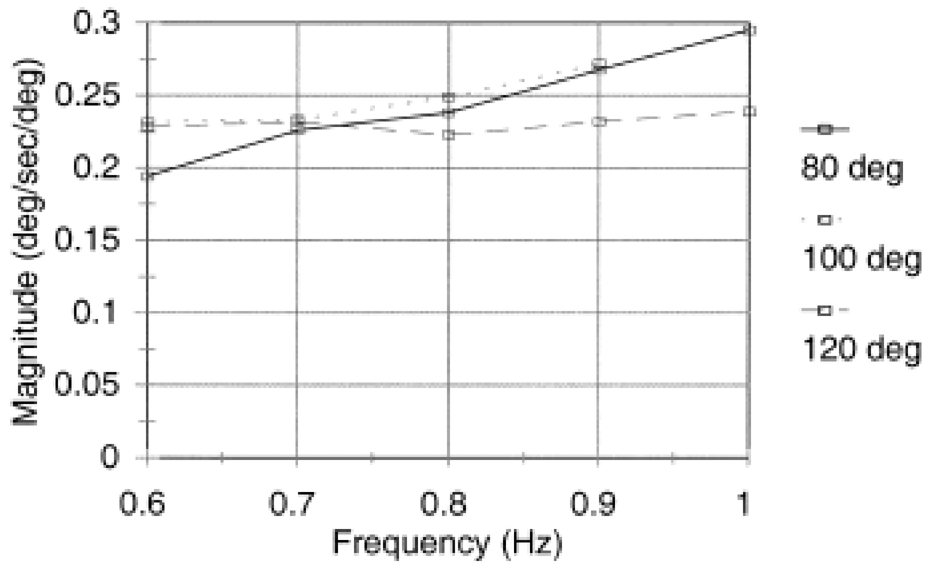


Figure 10.43 -- Roll Rate Frequency Response Using "Resonance" Steering Profile - 40 mph

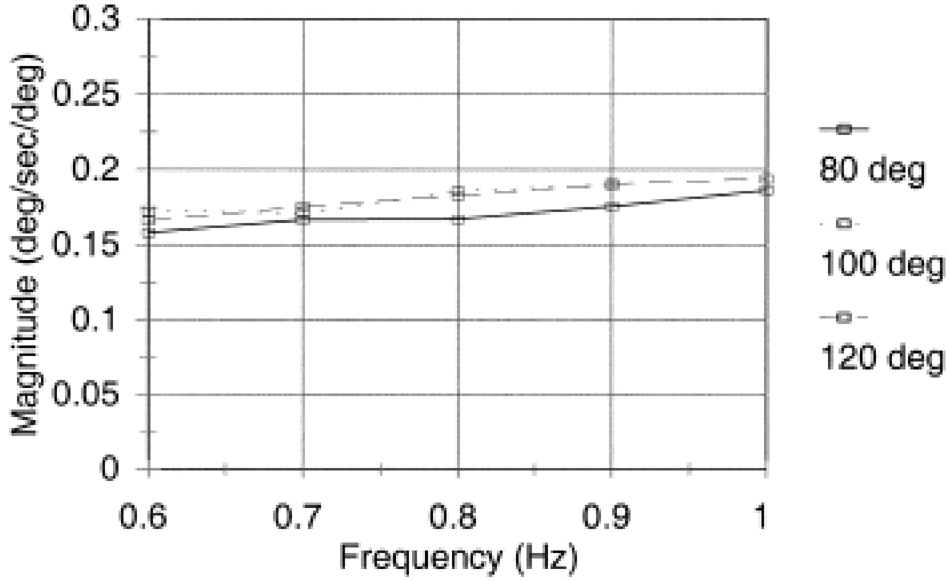


Figure 10.44 -- Yaw Rate Frequency Response Using "Resonance" Steering Profile - 40 mph

10.3.4 Summary of Resonant Steer Testing Using the Steering Controller Results

Pulse steering tests were performed using pulse durations of 0.2 and 0.3 seconds. The pulse magnitude was a nominal 80 degrees. Testing was conducted for both left and right steering directions and at 40 and 50 mph.

The right steer pulse generally produced a greater magnitude at the lower end of the frequency range for all four of the evaluated vehicle responses: lateral acceleration, roll angle, roll rate and yaw rate. The 0.2 and 0.3 second pulse duration gave very similar results. This suggests that either pulse duration would be appropriate for evaluating the vehicle for the frequency range of interest.

The magnitude portion of the curves are generally greater for the 50 mph tests compared to the 40 mph tests. This is especially true at the lower end of the frequency spectrum (<1.5 Hz). The phase angle response curves are very similar for both conditions. The 50 mph roll rate and yaw rate resonance peaks have a higher magnitude than that for the 40 mph test condition.

Sinusoidal sweep tests were performed using two sweep ranges: 0.1 to 1.0 Hz and 0.1 to 2.5 Hz. Testing was performed at two vehicle speeds: 40 and 50 mph.

The two frequency ranges tested produced very similar frequency response results in the range of overlap.

Except for some slight dips in a few of the frequency response curves, the pulse steer and sine sweep tests appear to produce very similar results.

The roll angle to steering angle frequency response did not have a strong resonance peak and was relatively flat over a wide frequency range (0.1 to 1.0 Hz) for both the pulse steer and sinusoidal sweep test results. The resonance test consists of applying multiple cycles of a sinusoidal input at a pre-determined natural frequency. Since a natural frequency could not be determined for roll angle due to its relatively flat response, a series of resonance type tests were performed at 0.6, 0.7, 0.8, 0.9, and 1.0 Hz to see if a more definite peak could be determined.

Performing resonance type tests did not produce a more definitive roll angle frequency response peak. Using a range of resonant steering profiles produced similar results to those found using the pulse steer and sinusoidal sweep steering profiles.

11.0 DEVELOPMENT OF THE PHASE II TEST MATRIX

This chapter presents the maneuvers for the Phase II test matrix and provides some detail for how they were selected. Two categories of testing will be performed: Vehicle Characterization Maneuvers and Untripped Rollover Propensity Maneuvers

The first four maneuvers that were performed for each test vehicle will be referred to as the Vehicle Characterization Maneuvers. As this name implies, the purpose of these maneuvers was to characterize the vehicle dynamics of each test vehicle. Each of the Vehicle Characterization Maneuvers will be described in detail in the following section of this chapter.

The final five maneuvers that were performed for each test vehicle in Phase II will be referred to as the Untripped Rollover Propensity Maneuvers. As this name implies, the purpose of these maneuvers was to determine each test vehicle's untripped rollover propensity. Each of the Untripped Rollover Propensity Maneuvers will be described in detail in the final section of this chapter.

11.1 Selection of Vehicle Characterization Maneuvers for Phase II Research

As the name implies, the purpose of the Vehicle Characterization Maneuvers is to characterize the vehicle dynamics of each test vehicle, i.e., determine some of the basic handling characteristics of the vehicle. There are two types of Vehicle Characterization Maneuvers. The first type can be used to determine the frequency response function of the test vehicle (a frequency response function is a non-linear system's analog of a transfer function; since a vehicle is not a linear system, it theoretically does not have a transfer function), i.e., to characterize each vehicle's transient dynamics. The second type can be used to measure the test vehicle's steady-state, lateral, dynamic properties.

Results from two of the Vehicle Characterization Maneuvers (the frequency response function determination maneuvers) were used to customize some of the five Untripped Rollover Propensity Maneuvers. Specifically, the roll angle natural frequency was used to determine the handwheel steering timing for two maneuvers, the Fishhook #1 and the Resonant Steer.

11.1.1 Frequency Response Test Methods

Two types of frequency response tests were developed: Pulse Steer and Sinusoidal Sweep. Both of these maneuvers excite a broad range of frequencies and can be used to calculate the frequency response functions for the vehicle.

The Pulse Steer maneuver collects data due to inputting a short, fairly large, handwheel steering pulse. Fast Fourier transform techniques are then applied to the data to calculate each vehicle's frequency response function.

For this maneuver, the vehicle is initially driven in a straight line. Starting at time 0.0, the Programmable Steering Machine generates a handwheel steering pulse. For this pulse, the steering handwheel is turned in 0.1 seconds from 0 to either ±80 degrees. Over the next 0.1 seconds, the steering handwheel is then turned back to 0 degrees. The steering handwheel is then held at 0 degrees for the remainder of the test. Figure 11.1 shows the desired steering handwheel angle as a function of time for this maneuver. From the results in Chapter 10, Pulse Steer testing was performed with 0.1 and 0.15 second rise and return times (0.2 and 0.3 seconds total respectively). The results showed very little difference between the two times. Also from the results in Chapter 10, the 80 degree value produced good results in prior testing and therefore was selected for use in Phase II testing.

Note that the values given above are the commanded values that are input to the Programmable Steering Machine. Due to the very large handwheel steering accelerations and velocities (800 degrees per second for ramping up and down, with infinite acceleration required at the peak of the triangular pulse) required to match the desired steering input, the Programmable Steering Machine cannot move the steering handwheel through precisely these values. However, Programmable Steering Machine does come fairly close to generating the desired inputs.

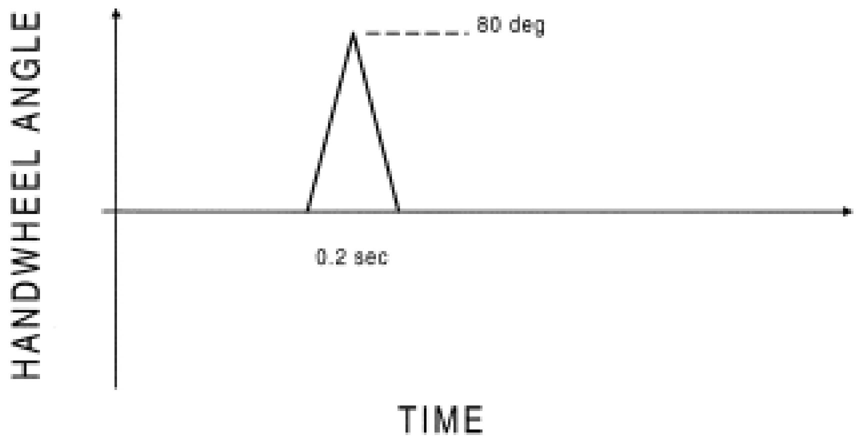


Figure 11.1 -- Pulse Steer Handwheel Input

This maneuver is performed at an initial speed of 50 mph. The test driver applies the throttle to try to hold the speed constant at 50 mph throughout the maneuver. From the results in Chapter 10, 40 and 50 mph tests produced results that were different in magnitude, but the basic shapes of the frequency response curves did not change and the resonance peaks did not shift dramatically. It was decided from a safety standpoint that several of the Untripped Rollover Propensity Tests would have a maximum test speed of 50 mph. The Resonance Steer test was to be conducted at 50 mph and therefore, the roll resonance needed to be determined for this speed. For these reasons, the test speed was set at 50 mph.

This maneuver is performed six times for each vehicle, three times with the initial steer direction being in each of the left and right directions. This does allow for the characterization of differences in left versus right steer vehicle performance.

The Sinusoidal Sweep maneuver collects data due to inputting a fixed amplitude, varying frequency handwheel steering sinusoid. Fast Fourier Transform techniques are then applied to the data to calculate each vehicle's frequency response function.

For this maneuver, the vehicle is initially driven in a straight line. Starting at time 0.0, the Programmable Steering Machine generates a $\pm$80 degree amplitude handwheel steering sinusoid the frequency of which linearly increases over 9.05 seconds from 0.1 to 1.5 Hertz. After 9.05 seconds, the frequency of the handwheel steering sinusoid linearly decreases during the next 9.05 seconds back to 0.1 Hertz. The test then terminates. Figure 11.2 shows the actual steering handwheel angle as a function of time for this maneuver.

This maneuver is performed at an initial speed of 50 mph. The test driver applies the throttle to try to hold the speed constant at 50 mph throughout the maneuver. This speed was chosen for the same reasons given above for the pulse steer maneuver. This maneuver is performed three times for each vehicle.

Even though the Sinusoidal Sweep and Pulse Steer produced essentially the same results in the Phase I-B testing, it was decided that both maneuvers would be used as a way of double checking the results.

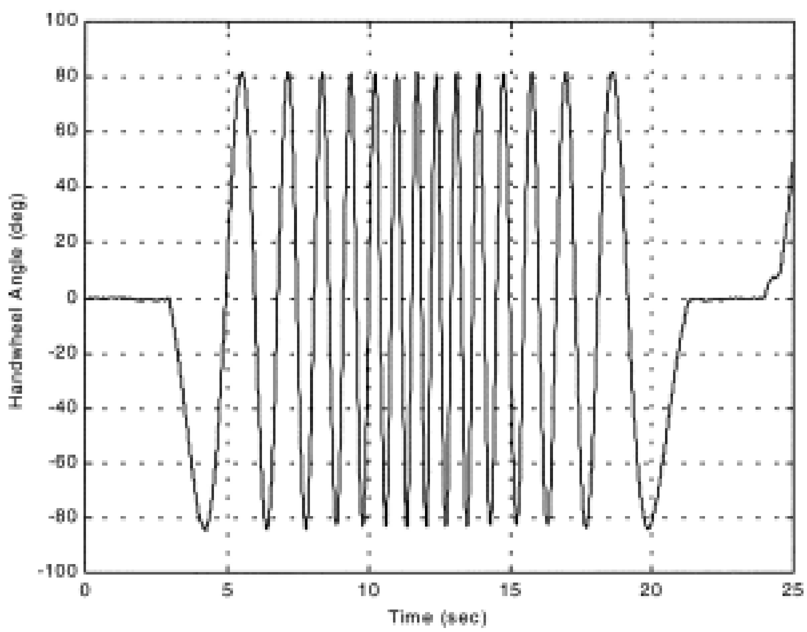


Figure 11.2 -- Handwheel Steering Input for the Sinusoidal Sweep Maneuver

11.1.2 Steady State, Lateral, Dynamic Test Methods

The Slowly Increasing Steer maneuver generates data by slowly increasing handwheel steering angle to allow the lateral dynamics of the vehicle to be characterized.

For this maneuver, the vehicle is initially driven in a straight line. Starting at time 0.0, the Programmable Steering Machine begins to linearly increase the handwheel steering angle over 20.0 seconds from 0 to either ±200 degrees. The test ends after 20.0 seconds. If the vehicle either ploughs-out, spins-out, or has two-wheel liftoff before the maximum handwheel steering angle is reached, the driver will prematurely terminate the test. Figure 11.3 shows the desired steering handwheel angle as a function of time for this maneuver.

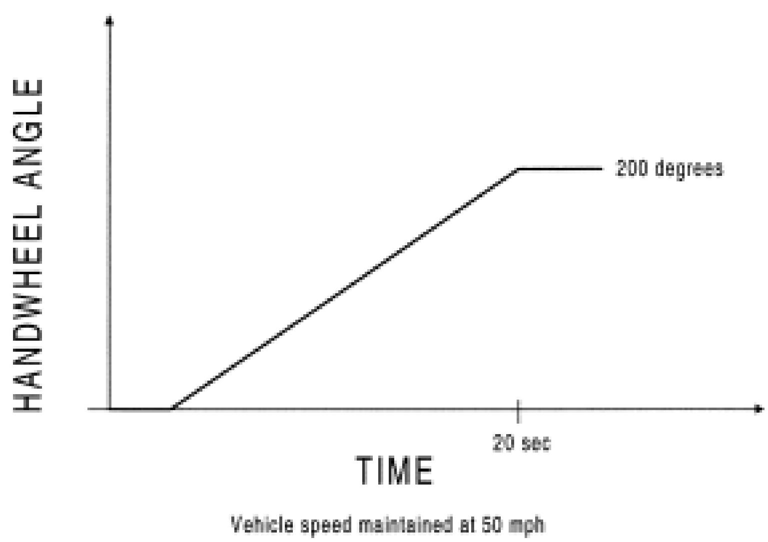


Figure 11.3 -- Slowly Increasing Steer Test Handwheel Input

This maneuver is performed at an initial speed of 50 mph. The test driver applies the throttle to try to hold the speed constant at 50 mph throughout the maneuver. Some vehicles cannot supply enough power to maintain the 50 mph speed with a large steering magnitude; the driver attains as high a speed as possible (in a reasonable period of time) and then terminates the test.

This maneuver is performed six times for each vehicle, three times with the steer direction being in each of the left and right directions.

The Slowly Increasing Speed maneuver generates data by slowly increasing the vehicle's speed with a fixed, non-zero handwheel steering angle to allow the lateral dynamics of the vehicle to be characterized.

For this maneuver, the vehicle is initially driven in a straight line at 35 mph. Starting at time 0.0, the Programmable Steering Machine increases the handwheel steering angle in 1.0 seconds from 0 to either ±A degrees. The value of A is determined from the Slowly Increasing Speed tests. It is the handwheel steering angle required to achieve a quasi-static lateral acceleration of 0.7 g. The handwheel steering angle is held fixed at ±A degrees from 1.0 seconds until the end of the test. The value of A would be decreased during the course of testing if a 50 mph speed could not be achieved with the given steering input. It would be lowered until a 50 mph speed could be achieved.

For the first 3.0 seconds after steering has been initiated, the driver uses throttle to try to hold speed constant at this speed. The driver then uses the throttle to accelerate the vehicle to 50 mph. Once 50 mph has been reached, the driver holds the vehicle at 50 mph for 5.0 seconds and then terminates the test. If the vehicle either ploughs-out, spins-out, or has two-wheel lift before the maximum vehicle speed is reached, the driver will prematurely terminate the test. Figure 11.4 shows the handwheel angle as a function of time for this maneuver.

This maneuver is performed six times for each vehicle, three times with the steer direction being in each of the left and right directions.

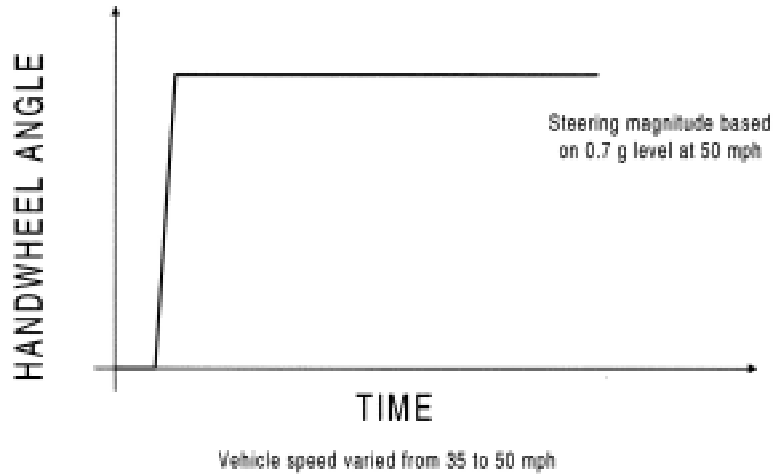


Figure 11.4 -- Slowly Increasing Speed Test Handwheel Input

11.2 Selection of Untripped Rollover Propensity Maneuvers for Phase II Research

The Untripped Rollover Propensity Maneuvers that will be used in Phase II will be described below. As this name implies, the purpose of these maneuvers was to determine each test vehicle's untripped rollover propensity. Each of the Untripped Rollover Propensity Maneuvers will be described in detail below. A comparison of Phase I-B results for the Fishhook with Pulse Braking, J-Turn with Pulse Braking, and

Fishhook without Pulse Braking is given first to provide some justification for selecting certain maneuvers and not others for further research.

11.2.1 Comparison of Fishhook with Pulse Braking Results to J-Turn with Pulse Braking and Fishhook without Pulse Braking Results

The Fishhook with Pulse Braking maneuver is fairly similar to the J-Turn with Pulse Braking maneuver except that the steering profile is a Fishhook instead of a J-Turn. The pulse braking application causes the same decrease in side-force capabilities for the tires as it did in the J-Turn with Pulse Braking maneuver. This decrease in side-force capabilities results in a similar decreases in vehicle responses followed by large increases in vehicle responses for both of these maneuvers. This can best be shown by examining test results from these two types of tests.

J-Turn with Pulse Braking (Test 295) results and Fishhook with Pulse Braking (Test 235) results are compared in Figures 11.5 and 11.6. The driver controlled steering and braking inputs for these tests are shown in Figure 11.5. The tests are aligned based on the timing of the pulse brake application for each test. The pulse brake peak magnitude for the J-Turn with Pulse Braking test (Test 295) is slightly higher in magnitude and duration than that for the Fishhook with Pulse Braking test (Test 235) and has a very similar shape. The negative steering magnitude for the two tests is fairly similar at the point of pulse brake application. The steering inputs prior to the Pulse Brake are very different for these two maneuvers.

The corrected lateral acceleration and roll angle traces for Tests 295 and 235 are plotted in Figure 11.6. The peak pre-pulse brake lateral acceleration is higher for Test 295 (J-Turn with Pulse). The dip in corrected lateral acceleration is greater for this test. This probably is primarily due to the larger pulse brake application. The peak post-pulse brake lateral accelerations are fairly similar for the two tests. Even though the lateral acceleration traces are fairly different up to the point of the pulse brake application, the general shape of the traces at the point of pulse brake and thereafter is very similar for the two tests. The roll angle trace for Test 235 reaches a higher peak prior to the brake pulse than that for Test 295. Both traces have a dip in value upon application of the brake pulse which is followed by post-pulse peak roll angles that are much higher than the pre-pulse peaks. Even though the peak and dip roll angle magnitudes are different, the general shape of the traces from the onset of the brake pulse and thereafter is very similar.

The Average, Standard Deviation, Coefficient of Variation, Minimum, and Maximum LAR values and the Number of Test Series for J-Turn with Pulse Braking, Fishhook without Pulse Braking, and Fishhook with Pulse Braking maneuvers are listed in Table 11.1. These values are generated using the Driver Controlled test results for the Ford Bronco II given in Chapter 7.

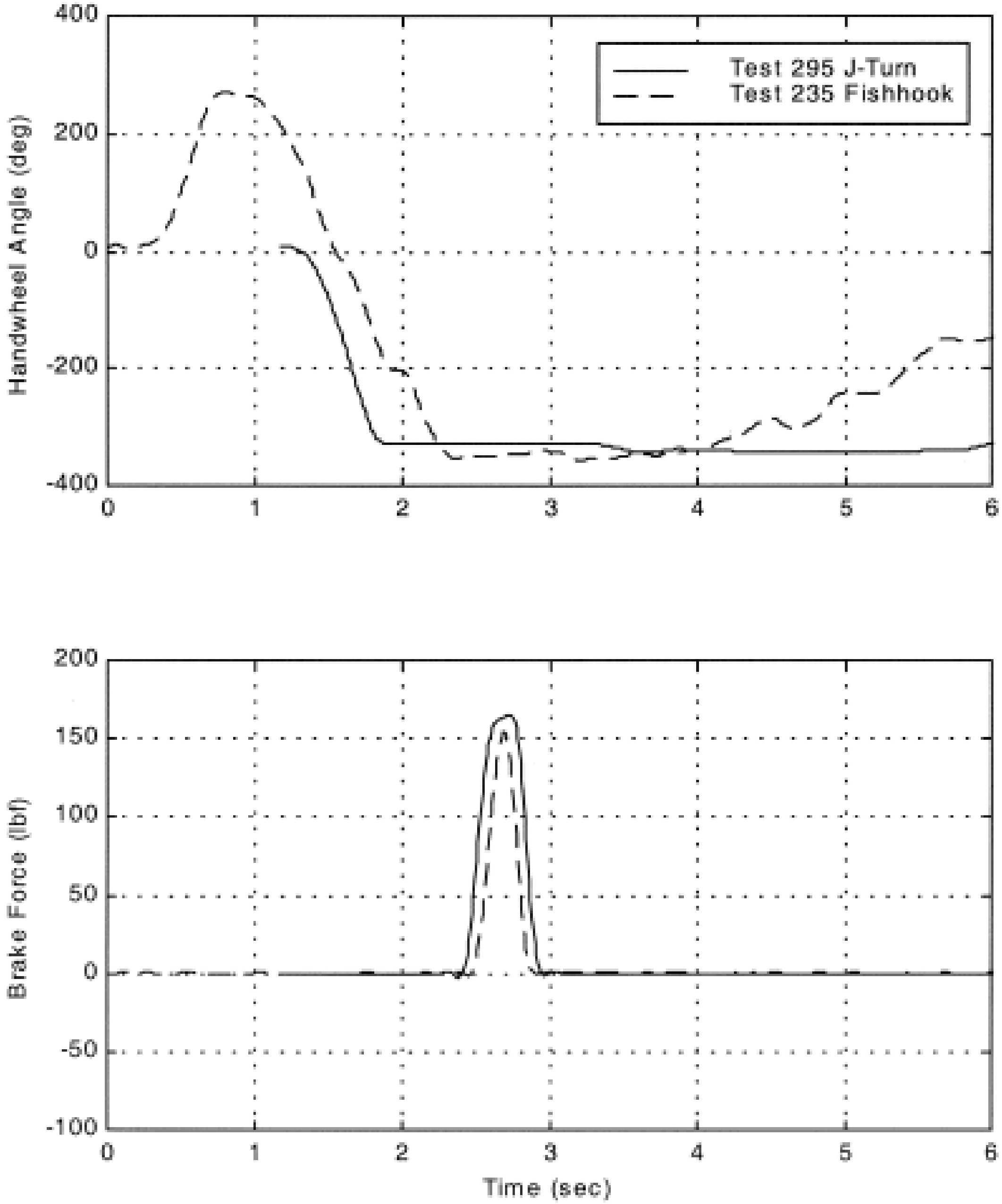


Figure 11.5 -- Comparison of Fishhook with Pulse Brake and J-Turn with Pulse Brake Results - Handwheel and Brake Pedal Inputs

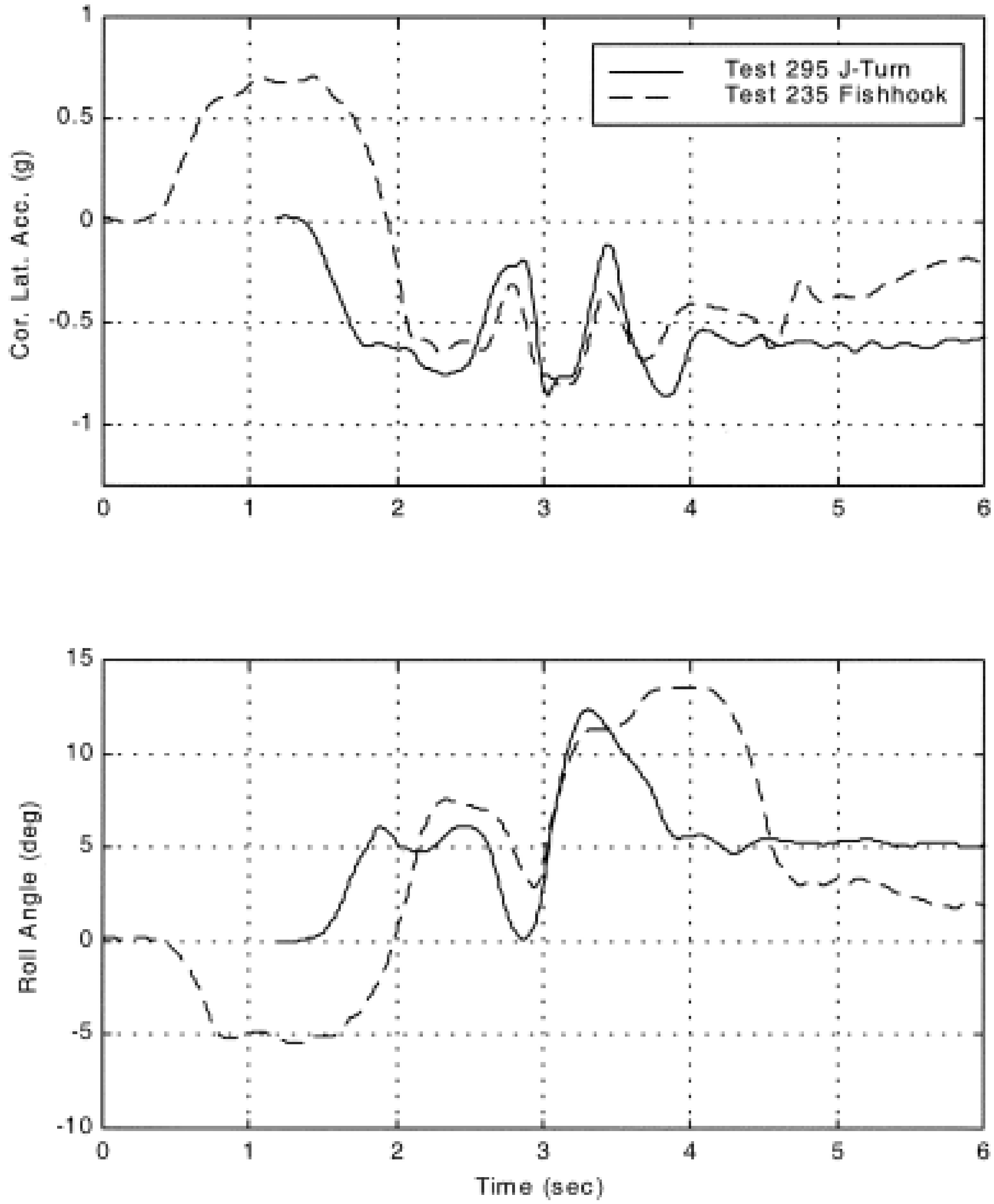


Figure 11.6 -- Comparison of Fishhook with Pulse Brake and J-Turn with Pulse Brake Results - Corrected Lateral Acceleration and Roll Angle Vehicle Response

The J-Turn with Pulse Brake and the Fishhook with Pulse Brake values are more similar to each other than they are to the Fishhook without Pulse Brake values. This is not surprising since the major mechanism for causing the two wheel lift is the same for these two maneuvers (pulse braking causing a decrease and then sudden increase in tire lateral-force characteristics).

The J-Turn with Pulse Braking maneuver had fewer test series conducted so the Standard Deviation and Coefficient of Variation values may be artificially low, but it appears that this maneuver is more repeatable than the Fishhook with Pulse Braking maneuver.

The range of LAR values for the Fishhook with Pulse Braking tests was larger than that found for the Fishhook without Pulse Braking tests. The range of LAR values for the J-Turn with Pulse Braking maneuver is much less than the other two maneuvers, but again fewer test series were run with the maneuver and therefore the range of values may be artificially low.

The results presented in this section suggest that the Fishhook with Pulse Braking maneuver does not provide any further information for determining the rollover propensity of vehicles than the J-Turn with Pulse Braking maneuver. It also appears to be less repeatable than other maneuvers. Therefore, it was decided that this maneuver would not be studied in Phase II of this rollover research program.

Table 11.1 -- Comparison of LAR Values for the J-Turn with Pulse Braking, Fishhook without Pulse Braking, and Fishhook with Pulse Braking Maneuvers

Maneuver	Steer Direction	Average LAR (g)	Standard Deviation (g)	Coef. of Variation (%)	Min (g)	Max (g)	No. of Test Series
J-Turn w/ Pulse	Right	0.86	0.006	0.7	0.86	0.87	3
	Left	-0.83	0.017	2.1	-0.82	-0.85	3
Fishhook w/o Pulse	Left/Right	0.76	0.014	1.9	0.75	0.78	4
	Right/Left	-0.72	0.023	-3.3	-0.70	-0.76	5
Fishhook w/ Pulse	Left/Right	0.83	0.031	3.7	0.78	0.86	5
	Right/Left	-0.82	0.046	-5.7	-0.76	-0.87	5

11.2.2 Test Procedures for Untripped Rollover Propensity Determination Maneuvers

The five Untripped Rollover Propensity Maneuvers are: J-Turn, J-Turn with Pulse Brake, Fishhook 1, Fishhook 2, and Resonant Steer. Details for how each of these maneuvers were developed and how they will be implemented in Phase II are given in this section.

The J-Turn (without pulse braking) maneuver determines vehicle rollover propensity by suddenly making a large turn. Following the sudden turn, the steering handwheel is held fixed for the remainder of the test. This maneuver models, in an extreme way, what might happen when a driver initiates a severe turn (such as onto a cloverleaf ramp). According to [6], the handwheel steering angles and rates used are, while extreme, within the capabilities of drivers. The average steering rate supplied by the controller is greater than that found for the drivers in the Phase I-B testing however.

For this maneuver, the vehicle is initially driven in a straight line. Starting at time 0.0, the Programmable Steering Machine turns the steering handwheel in 0.33 seconds from 0 to ±330 degrees. The steering handwheel is then held at 330 degrees for the remaining 4.67 seconds of the test. Figure 11.7 shows the desired steering handwheel angle as a function of time for this maneuver.

This maneuver is performed at initial speeds ranging from 36 to 60 mph. The test driver releases the throttle after the steering input has been applied (i.e., he does not attempt to hold the vehicle's speed constant during the test).

Initial speed is used as a severity parameter for this maneuver. The initial speed is increased from run-to-run from 36 to 60 mph in approximately 2 mph increments (unless a termination condition occurs). Two series of tests are conducted: one with the initial turn direction to the left and one with it to the right.

The J-Turn With Pulse Braking maneuver determines vehicle rollover propensity by suddenly making a large turn which is followed by pulse braking. This maneuver models what might happen when a driver sharply brakes for a short period of time shortly after initiating a severe turn.

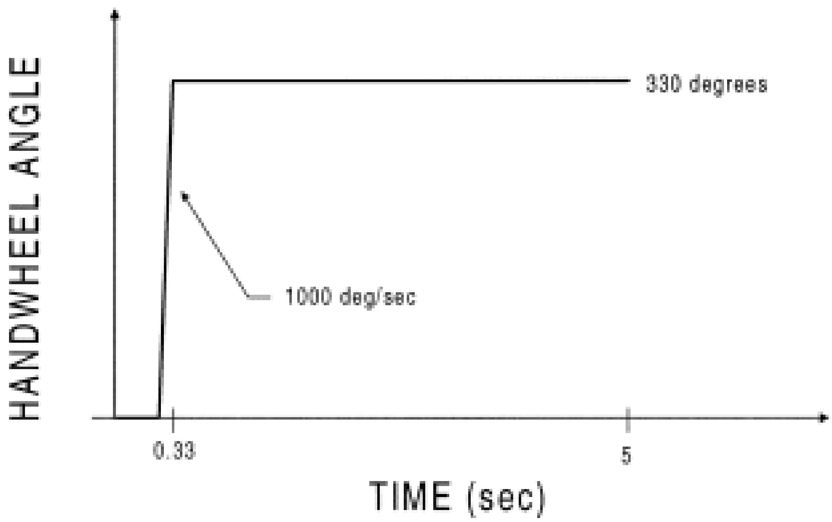


Figure 11.7 -- J-Turn and J-Turn with Pulse Brake Handwheel Input

For this maneuver, the steering handwheel inputs are identical to those of the J-Turn (without pulse braking) maneuver. Figure 11.7 again shows the desired steering handwheel angle as a function of time for this maneuver.

The maneuver differs from the J-Turn in that approximately 1.0 seconds after the completion of handwheel steering motion, the brake pedal is sharply pulsed. The Vehicle Research and Test Center did not have a machine that could provide a consistent pulse to the brake pedal during Phase II testing, therefore, this input was generated by the test driver. The driver's instructions are to depress the brake pedal with approximately 200 pounds force as rapidly as possible and then immediately release the pedal. Figure 11.8 shows the desired brake pedal force as a function of time for this maneuver. The test driver practiced pulsing the brake pedal before testing any vehicles for this program. To assist the driver, a buzzer is set to sound at the time when pulse braking is to be initiated.

If a test vehicle has ABS brakes, they are kept operational for this maneuver. This differs from past practice in which ABS brakes were disabled for maneuvers involving pulse braking.

This maneuver is performed at initial speeds ranging from 36 to 60 mph. The test driver applies the throttle to try to hold the speed constant at the desired initial speed until the pulse brake application at which point the throttle is released.

Initial speed is used as a severity parameter for this maneuver. The initial speed is increased from run-to-run from 36 to 60 mph in approximately 4 mph increments (unless a termination condition occurs). Two series of tests are conducted: one with the initial turn direction to the left and one with it to the right.

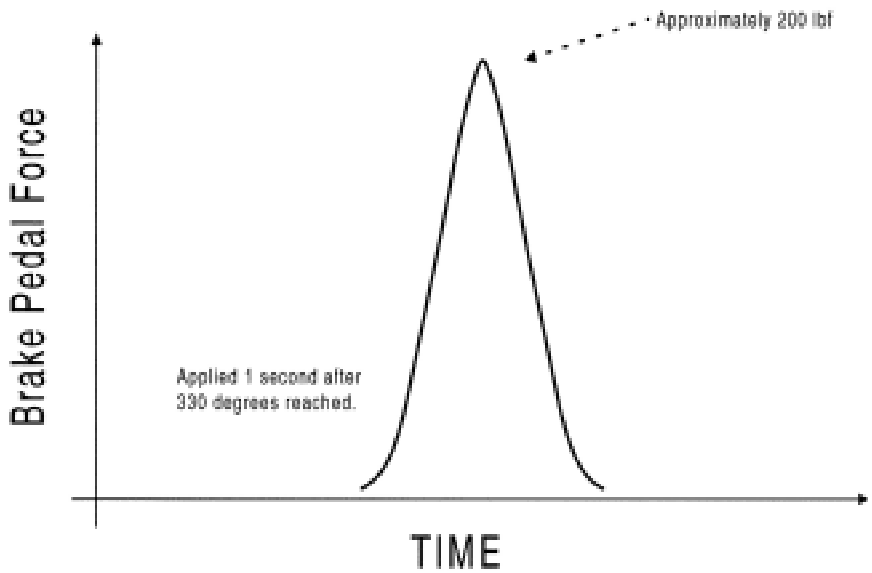


Figure 11.8 -- J-Turn with Pulse Braking - Pulse Shape

Initial speed is used as a severity parameter for this maneuver. The initial speed is increased from run-to-run from 36 to 60 mph in approximately 4 mph increments (unless a termination condition occurs). Two series of tests are conducted: one with the initial turn direction to the left and one with it to the right.

The Fishhook #1 maneuver attempts to induce two-wheel lift or rollover at a lower lateral acceleration than the J-Turn by suddenly making a large turn and then turning back even farther in the opposite direction. Following the second turn, the steering handwheel is held fixed for the remainder of the test.

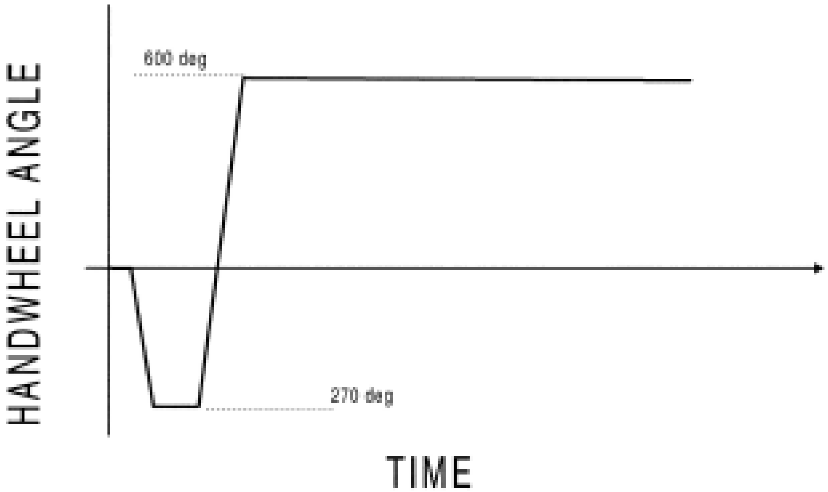
This maneuver models, in an extreme way, what might happen when a driver performs a double lane change or two-wheels off-road recovery maneuver. According to [6], the handwheel steering angles and rates used are, while extreme, within the capabilities of drivers.

The fishhook maneuver was originally developed by Toyota Motor Corporation. It is fully described in Toyota Engineering Standard TS-A1544 [2].

This maneuver, as performed by Toyota and by the Vehicle Research and Test Center during Phases I-A and I-B of the Light Vehicle Research Program, used driver generated handwheel steering inputs. However, the handwheel steering inputs for the Phase II research were to be generated by the Programmable Steering Machine. The Programmable Steering machine does not comprehend instructions such as "Turn as quickly as possible to 270 degrees." Therefore, the authors had to translate the handwheel steering input for the fishhook into a precisely defined handwheel steer angle as a function of time.

There are many possible ways to translate the handwheel steering input for the fishhook into a precisely defined handwheel steer angle as a function of time. The authors' goal when developing the handwheel steer angle as a function of time for the Fishhook #1 maneuver was to select a function that (1) approximately matched many of the steering handwheel angle versus time traces that were measured during the Phases I-A and I-B testing and that (2) would, in the judgement of the authors, result in two-wheel lift or rollover at the lowest possible speed.

Figure 11.9 shows the desired steering handwheel angle as a function of time for the Fishhook #1 maneuver while Table 11.2 lists the desired steering handwheel angles at specified instants in time. Note that selected times used in this maneuver are chosen according to the roll natural frequency of the vehicle being tested. Time B is one-fourth of the inverse of the vehicle's roll angle natural frequency (in Hertz) that was determined during the frequency response measurement testing. From the Fishhook Controller Study 2, the 0.25 second and 0.5 second dwell time tended to produce the greatest peak value vehicle responses. A 0.5 second delay would be too long to accommodate the roll natural frequency of the vehicle which is why the 0.25 second dwell time was chosen.



Steering Rates Based on Roll Natural Frequency

Figure 11.9 -- Fishhook #1 Handwheel Input

Table 11.2 -- Value of Handwheel Steering Angle at Selected Instants for the Fishhook #1 Maneuver	
Time (sec)	Handwheel Angle (deg)
0.000	0.0
B ! 0.125	270.0
B % 0.125	270.0
2 (B	0.0
2 (B % 0.80	-600.0
5.000 (End of Test)	-600.0

This maneuver is performed with entrance speeds ranging from 34 to 50 mph. The test driver releases the throttle at the beginning of the test (i.e., he does not attempt to hold the vehicle's speed constant during the test).

Initial speed is used as a severity parameter for this maneuver. The initial speed is increased from run-to-run from 34 to 50 mph in approximately 2 mph increments (unless a termination condition occurs). Two series of tests are conducted: one with the initial turn direction to the left and one to the right.

The Fishhook #2 maneuver, as with Fishhook #1, attempts to induce two-wheel lift or rollover at a lower lateral acceleration than the J-Turn by suddenly making a large turn and then turning back even farther in the opposite direction. Following the second turn, the steering handwheel is held fixed for the remainder of the test. Although the motivation of the two fishhook maneuvers is identical, the steering movements of Fishhook #2 differ from those used in Fishhook #1 in several subtle ways.

Fishhook #2 is designed to approximate a driver's steering response during a two-wheel off road recovery maneuver based on research conducted by the Texas Transportation Institute (TTI) [7]. Rather than using a fixed 270 degree initial steering input as specified by Toyota Engineering Standard TS-A1544, Fishhook #2 utilizes an initial steering angle of 7.5 times the Overall Steering Ratio of a given vehicle. The timing of the steering reversal is also different from that used in the Fishhook #1 maneuver, as all handwheel rates for Fishhook #2 are 500 degrees per second.

Figure 11.10 shows the desired steering handwheel angle as a function of time for the Fishhook #2 maneuver while Table 11.3 lists the desired steering handwheel angles at specified instants in time.

This maneuver is performed at initial speeds ranging from 34 to 50 mph. The test driver releases the throttle at the beginning of the test (i.e., he does not attempt to hold the vehicle's speed constant during the test).

Table 11.3 -- Value of Handwheel Steering Angle at Selected Instants for the Fishhook #2 Maneuver	
Time (sec)	Handwheel Angle (deg)
0.000	0.0
C) 500.0	& C
C) 500.0 % 0.500	& C
(2 (C)) 500.0 % 0.500	0.0
(2 (C)) 500.0 % 1.700	600.0
5.000 (End of Test)	600.0

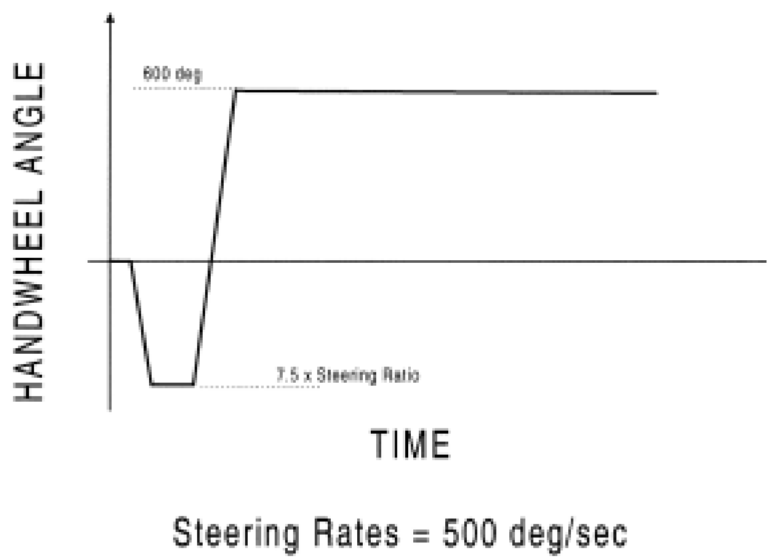


FIGURE 11.10: Fishhook #2 Handwheel Input

Initial speed is used as a severity parameter for this maneuver. The initial speed is increased from run-to-run from 34 to 50 mph in approximately 2 mph increments (unless a termination condition occurs).

Two series of tests are conducted: one with the initial turn direction to the left and one with it to the right.

Angle C is equal to the handwheel steering angle necessary to achieve a road wheel steering angle of 7.5 degrees. Angle C is measured with the front wheels of the vehicle on a low-friction plate.

Figure 11.11 shows a comparison of the Fishhook #1 and #2 maneuvers. The Fishhook #1 has a faster steering rate (750 vs. 500 deg/sec), a generally larger first steer magnitude, and a shorter dwell time after the first steer. From the Fishhook Controller Study 2, the 0.25 second and 0.5 second dwell time tended to produce the greatest peak value vehicle responses. The 0.5 second dwell time was chosen for the Fishhook #2 to provide more of a contrast to the Fishhook #1. The second steer magnitude is the same at 600 degrees. Note that both maneuvers end at approximately 8 seconds in Figure 11.11. The steering movements occurring in the 8 to 10 second range are from the driver resuming control of the vehicle and do not affect the test results.

The Resonant Steer maneuver is designed to excite a vehicle's roll natural frequency, as determined by the Pulse Steer and Sinusoidal Sweep Vehicle Characterization Maneuvers.

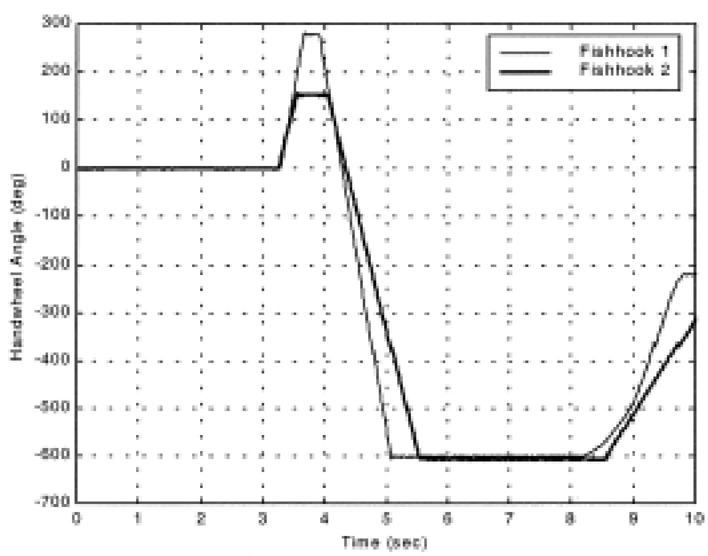


Figure 11.11 -- Comparison of Handwheel Angle Steering Inputs for the Fishhook 1 and Fishhook 2 Maneuvers

For this maneuver, the test vehicle is initially driven in a straight line. Starting at time 0.0, the Programmable Steering Machine begins to turn the handwheel back-and-forth through multiple cycles in a sinusoidal manner. The frequency of sinusoidal steering input is equal to each vehicle's roll natural frequency, and the amplitude is varied on a run-to-run basis from ±75 degrees to ±180 degrees (unless a termination condition occurs). If a termination condition is not encountered, the test ends after 20.0 seconds. If the vehicle ploughs-out, spins-out, or experiences two-wheel lift, the driver will prematurely terminate the test. Figure 11.12 shows a typical steering handwheel input as a function of time for this maneuver.

This maneuver is performed at an initial speed of 50 mph. The test driver applies the throttle in an attempt to hold vehicle speed constant at 50 mph throughout the maneuver.

This maneuver is performed once for each of the nine steering amplitudes, for each vehicle, until a termination condition is encountered. The initial steering angle direction is not specified, rather the test driver chooses an initial left or right steering input based on the anticipated path the vehicle may deviate to at maneuver completion.

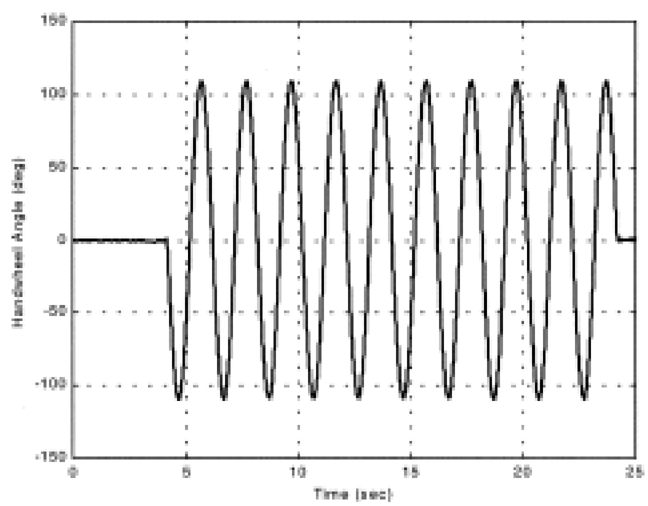


Figure 11.12 -- Handwheel Steering Input for the Resonant Steer Maneuver

12.0 CONCLUSIONS

Driver variability effects on test results were evaluated with four test maneuvers: J-Turn (Without Pulse Braking), J-Turn with Pulse Braking, Fishhook Without Pulse Braking, and Fishhook with Pulse Braking.

- Increasing J-Turn severity, by increasing steering magnitude or vehicle speed, resulted in increasing lateral acceleration and roll angle up to the point of limit response.
- The J-Turn maneuver was found to be fairly repeatable. For all groups of repeatability tests (similar speed, handwheel inputs, and throttle), the resulting maximum lateral accelerations and maximum roll angles were very similar.
- Throttle position did appear to make a large difference in J-Turn test results. To reduce the amount of variability in future testing, the drivers will release the throttle upon the initiation of the steering input.
- Driver differences were notable for the J-Turn with Pulse Braking tests, and while these differences produced test-to-test variations, the overall test results for each driver were fairly similar. The Minimum Initial Speeds Required to Produce Two-Wheel Lift were in the same range for the two drivers. The LAR values for each combination of steering direction, driver, and test set were very similar as well.
- Driver variability did not seem to influence the Fishhook test results for the 1990 Toyota 4Runner. The LAR and Minimum Initial Vehicle Speed Required to Produce Two-Wheel Lift values were very similar for the three drivers.
- The 1984 Ford Bronco II Fishhook test results were more scattered, but this scatter appeared to be related more to tire wear (on the shoulder) issues than it did to driver differences. The shoulder wear produced during testing is not similar to normal wear on a tire seen in real world driving conditions.
- The Fishhook with Pulse Braking maneuver is fairly similar to the J-Turn with Pulse Braking maneuver except that the steering profile is a Fishhook instead of a J-Turn. The pulse braking

- The driver controlled results suggest that the Fishhook with Pulse Braking maneuver did not provide any further information for determining the rollover propensity of vehicles than the J-Turn with Pulse Braking maneuver and was less repeatable than other maneuvers. Therefore, it was decided that this maneuver would not be studied in Phase II.

Outrigger effects were studied using three different maneuvers: the Fishhook Without Pulse Braking, the Fishhook With Pulse Braking, and Sinusoidal Sweep. Up to three outrigger conditions were evaluated with each maneuver: Ballasted outriggers, normal outriggers (Unballasted), and/or no outriggers.

- For the Fishhook Without Pulse Braking tests, the ballast added to the outriggers did not appear to have a strong effect on the calculated LAR values.
- There appeared to be two main differences in the vehicle responses for the two outrigger conditions. The Ballasted outriggers produced larger peak roll rates during the steering reversal than the Unballasted outriggers. The Ballasted outriggers also maintained a much larger roll angle during the "steady state" portion after the steering reversal than the Unballasted outriggers.
- Very limited Fishhook with Pulse Braking tests were performed with Ballasted outriggers so no definitive conclusions could be drawn. To properly evaluate the effect of outriggers on individual tests with the Fishhook with Pulse Brake maneuver would require the use of a steering and braking controller that could provide repeatable steering and braking inputs.
- Sinusoidal Sweep tests results were studied using frequency domain techniques. The outriggers tend to dampen the response at higher frequencies and increase the response at lower frequencies. These changes appear to be relatively small especially for the normal outrigger case versus the no outrigger case.

Two drivers performed both low fuel and full fuel level tests with the 1990 Toyota 4Runner.

- Fuel level did not appear to have a strong influence on test results. The LAR and Minimum Initial Speed Required to Produce Two-Wheel Lift values were very similar for the two fuel level conditions.
- Since there appears to be no major difference in response, all testing in Phase II will be done with a full fuel level for testing convenience.

Steering controller tests were performed using three maneuvers: J-Turn with Pulse Braking, Fishhook without Pulse Braking, and Resonant Steer.

- For the first part of the J-Turn with Pulse Braking steering controller study, two sets of tests were performed to see the effect of a lower brake pedal force versus a higher brake pedal force on overall results.
- The Peak Post-Pulse vehicle responses were generally higher for the higher brake force tests.
- For the second part of the J-Turn with Pulse Braking steering controller study, the test speed was kept constant and the driver was asked to provide varying levels of brake pedal force.
- In agreement with the first part of this study, the Peak Post-Pulse vehicle responses measured during the second part of this study tended to increase with increasing brake pedal force.
- The first steering controller Fishhook Profile study compared two steering profiles by running complete Fishhook test sets so an appropriate LAR could be determined.
- The LAR values for the two steering profiles were very similar for the two steer directions. The minimum speed required to produce two-wheel lift were also very similar.
- For the second Fishhook Profile study, two levels of handwheel rate were used (500 and 750 deg/sec) and four levels of pause between initial and second steer (0, 0.25, 0.5, and 1.0 sec). Four replications were conducted and the tests were performed in a random order for each replication. In very broad terms, the 750 deg/sec handwheel rate generally produced greater peak

values than the 500 deg/sec rate. Also in broad terms, the 0.25 and 0.50 second pause values tended to produce greater peak values than the 0 and 1 second pause values.

- The test results from the second Fishhook profile study showed that the steering controller produces very repeatable steering inputs and that the corresponding vehicle responses can be very repeatable.
- The resonance test consists of applying multiple cycles of a sinusoidal input at a pre-determined natural frequency. This natural frequency can be determined using pulse, sinusoidal sweep, or a series of fixed frequency test methods.
- A comparison of pulse steer, sinusoidal sweep, and a series of fixed frequency test results showed that, except for some slight dips in a few of the frequency response curves, the tests appear to produce very similar results.

Two categories of testing will be performed in Phase II: Vehicle Characterization Maneuvers and Untripped Rollover Propensity Maneuvers. As the name implies, the purpose of the Vehicle Characterization Maneuvers is to characterize the vehicle dynamics of each test vehicle, i.e., determine some of the basic handling characteristics of the vehicle. There are two types of Vehicle Characterization Maneuvers. The first type can be used to determine the frequency response function to characterize the test vehicle transient dynamic response. The second type can be used to measure the test vehicle's steady-state, lateral, dynamic properties.

- The Pulse Steer maneuver collects data due to inputting a short, fairly large, handwheel steering pulse.
- The Sinusoidal Sweep maneuver collects data by inputting a fixed amplitude, varying frequency handwheel steering sinusoid.
- For either the Pulse Steer or Sinusoidal Sweep maneuver, Fast Fourier Transform techniques are applied to the data to calculate each vehicle's frequency response function.

- Even though the Sinusoidal Sweep and Pulse Steer produced essentially the same results in the Phase I-B testing, it was decided that both maneuvers would be used as a way of double checking the results.
- The Slowly Increasing Steer maneuver collects data by slowly increasing handwheel steering angle to allow the lateral dynamics of the vehicle to be characterized.
- The Slowly Increasing Speed maneuver collects data by slowly increasing the vehicle's speed with a fixed, non-zero handwheel steering angle to allow the lateral dynamics of the vehicle to be characterized.

The five Untripped Rollover Propensity Maneuvers are: J-Turn, J-Turn with Pulse Brake, Fishhook 1, Fishhook 2, and Resonance Steer.

- The J-Turn (without pulse braking) maneuver determines vehicle rollover propensity by suddenly making a large turn. Following the sudden turn, the steering handwheel is held fixed for the remainder of the test. This maneuver models, in an extreme way, what might happen when a driver initiates a severe turn.
- The J-Turn With Pulse Braking maneuver determines vehicle rollover propensity by suddenly making a large turn which is followed by pulse braking. This maneuver models what might happen when a driver sharply brakes for a short period of time shortly after initiating a severe turn.
- The Fishhook #1 maneuver attempts to induce two-wheel lift or rollover at a lower lateral acceleration than the J-Turn by suddenly making a large turn and then turning back even farther in the opposite direction. Following the second turn, the steering handwheel is held fixed for the remainder of the test. This maneuver models, in an extreme way, what might happen when a driver performs a double lane change or two-wheels off-road recovery maneuver.
- The Fishhook #2 maneuver has a very similar steering profile to that used for the Fishhook #1 maneuver (steer in one direction, pause, reverse steering direction, and hold). The steering rates and amplitudes and the pause durations for the two maneuvers are generally different. The steering reversals for the Fishhook #1 and #2 maneuvers are designed to try and induce two-

wheel lift or rollover at a lower lateral acceleration and/or speed than the single turn J-Turn maneuver.

- The Resonant Steer maneuver is designed to excite the vehicle roll natural frequency, as determined by the Pulse Steer and Sinusoidal Sweep Vehicle Characterization Maneuvers, by applying a sinusoidal steering input at the predetermined natural frequency.

13.0 REFERENCES

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Appendix A: Driver Controlled Fishhook Maneuver -

Individual Test Results

Table A.1 - Driver Controlled Toyota 4Runner Fishhook Test Results - Maximum Corrected Lateral Acceleration and Roll Angle Values

Run Number	Driver	Tires	Outrigger Ballast	Fuel Level	Speed (mph)	1st Roll Peak after Steer Reversal			2nd Roll Peak after Steer Reversal		
						Roll Angle (deg)	Cor. Lat. Acc. (g)	Two-Wheel Lift	Roll Angle (deg)	Cor. Lat. Acc. (g)	Two-Wheel Lift
30	A	Large	no	Low	38.3	8.5	-0.67	no	9.4	-0.77	no
31	A	Large	no	Low	38.7	8.8	-0.67	no	10.6	-0.78	yes
32	A	Large	no	Low	35.0	8.7	-0.65	no	9.3	-0.78	yes
33	A	Large	no	Low	38.3	9.2	-0.71	yes	9.6	-0.80	yes
34	A	Large	no	Low	36.8	10.9	-0.70	yes	9.9	-0.80	yes
36	A	Large	no	Low	35.2	7.5	-0.67	no	7.8	-0.69	no
37	A	Large	no	Low	36.5	10.6	-0.71	yes	10.4	-0.80	yes
38	A	Large	no	Low	35.1	9.7	-0.68	yes	8.0	-0.73	no
40	A	Large	no	Low	34.1	-8.2	0.62	no	-9.0	0.74	yes
41	A	Large	no	Low	35.2	-8.5	0.64	no	-8.4	0.78	yes
45	A	Large	no	Low	33.3	-7.5	0.66	no	-7.6	0.65	no
46	A	Large	no	Low	34.0	-7.7	0.68	no	-8.1	0.67	no
47	A	Large	no	Low	37.1	-8.1	0.72	no	-9.1	0.75	no
48	A	Large	no	Low	38.6	-8.9	0.65	yes	-9.5	0.77	yes
49	A	Large	no	Low	38.6	-9.8	0.67	yes	-8.6	0.76	yes
50	A	Large	no	Low	38.0	-8.9	0.66	yes	-9.0	0.76	no
51	A	Large	no	Low	36.8	-8.6	0.63	no	-9.2	0.76	yes
52	A	Large	no	Low	37.6	-9.9	0.68	yes	-8.4	0.76	yes
53	A	Large	no	Low	36.7	-8.7	0.65	yes	-9.1	0.75	yes
55	A	Large	no	Low	32.9	8.6	-0.65	no	9.1	-0.77	no
56	A	Large	no	Low	36.0	4.3	-0.35	no	4.1	-0.43	no
57	A	Large	no	Low	35.9	10.4	-0.70	yes	8.7	-0.76	no
58	A	Large	no	Low	35.2	9.4	-0.67	yes	8.9	-0.80	no

Table A.1 - Driver Controlled Toyota 4Runner Fishhook Test Results - Maximum Corrected Lateral Acceleration and Roll Angle Values

Run Number	Driver	Tires	Outrigger Ballast	Fuel Level	Speed (mph)	1st Roll Peak after Steer Reversal			2nd Roll Peak after Steer Reversal		
						Roll Angle (deg)	Cor. Lat. Acc. (g)	Two-Wheel Lift	Roll Angle (deg)	Cor. Lat. Acc. (g)	Two-Wheel Lift
59	A	Large	no	Low	36.8	12.4	-0.74	yes	8.6	-0.79	no
60	A	Large	no	Low	36.6	11.7	-0.72	yes	7.5	-0.77	no
61	A	Large	no	Low	34.5	9.5	-0.68	yes	8.0	-0.75	no
67	B	Large	no	Low	33.9	8.0	-0.62	no	8.7	-0.68	no
68	B	Large	no	Low	35.0	8.2	-0.64	no	9.0	-0.73	no
69	B	Large	no	Low	36.3	7.4	-0.70	no	7.7	-0.69	no
70	B	Large	no	Low	35.5	9.6	-0.68	yes	9.7	-0.78	yes
71	B	Large	no	Low	37.1	9.7	-0.69	yes	9.3	-0.77	no
72	B	Large	no	Low	37.2	9.6	-0.71	yes	8.6	-0.78	no
73	B	Large	no	Low	38.4	11.4	-0.73	yes	9.5	-0.77	yes
74	B	Large	no	Low	38.1	11.7	-0.71	yes	11.7	-0.70	no
75	B	Large	no	Low	33.3	-7.5	0.67	no	-7.7	0.67	no
76	B	Large	no	Low	32.9	-7.4	0.67	no	-7.7	0.67	no
77	B	Large	no	Low	33.2	-7.3	0.67	no	-7.5	0.67	no
78	B	Large	no	Low	35.4	-8.2	0.73	no	-8.9	0.77	yes
79	B	Large	no	Low	36.2	-8.0	0.72	no	-8.5	0.72	no
80	B	Large	no	Low	37.7	-8.7	0.66	yes	-10.5	0.76	yes
81	B	Large	no	Low	37.6	-8.9	0.66	yes	-8.8	0.76	yes
84	C	Large	no	Low	31.1	-6.1	0.61	no	-7.0	0.64	no
85	C	Large	no	Low	30.8	-7.1	0.66	no	-7.9	0.65	no
86	C	Large	no	Low	31.5	-6.9	0.66	no	-7.6	0.66	no
87	C	Large	no	Low	32.5	-6.8	0.66	no	-7.7	0.66	no
88	C	Large	no	Low	34.0	-7.5	0.66	no	-7.6	0.68	no

Table A.1 - Driver Controlled Toyota 4Runner Fishhook Test Results - Maximum Corrected Lateral Acceleration and Roll Angle Values

Run Number	Driver	Tires	Outrigger Ballast	Fuel Level	Speed (mph)	1st Roll Peak after Steer Reversal			2nd Roll Peak after Steer Reversal		
						Roll Angle (deg)	Cor. Lat. Acc. (g)	Two-Wheel Lift	Roll Angle (deg)	Cor. Lat. Acc. (g)	Two-Wheel Lift
89	C	Large	no	Low	35.0	-7.4	0.70	no	-8.0	0.71	no
90	C	Large	no	Low	35.0	-7.2	0.68	no	-7.3	0.70	no
91	C	Large	no	Low	36.0	-7.2	0.69	no	-8.7	0.71	no
92	C	Large	no	Low	36.2	-7.6	0.69	no	-8.7	0.72	no
93	C	Large	no	Low	38.0	-7.6	0.67	no	-8.8	0.71	yes
94	C	Large	no	Low	37.8	-8.2	0.66	yes	-7.8	0.79	yes
95	C	Large	no	Low	30.6	8.2	-0.62	no	8.6	-0.68	no
96	C	Large	no	Low	32.5	9.5	-0.64	yes	9.4	-0.75	no
97	C	Large	no	Low	32.7	8.6	-0.64	no	8.5	-0.70	no
98	C	Large	no	Low	34.2	10.1	-0.64	yes	9.5	-0.76	no
99	C	Large	no	Low	35.0	10.3	-0.66	yes	9.5	-0.74	no
105	C	Large	no	Low	34.0	9.5	-0.64	no	8.5	-0.71	no
106	C	Large	no	Low	35.0	9.8	-0.67	yes	10.0	-0.76	yes
107	C	Large	no	Low	36.0	9.5	-0.68	yes	9.4	-0.78	yes
108	C	Large	no	Low	36.6	10.3	-0.67	yes	9.7	-0.78	yes
109	C	Large	no	Low	37.1	10.7	-0.70	yes	9.5	-0.66	yes
110	C	Large	no	Low	33.8	-7.2	0.67	no	-7.2	0.67	no
111	C	Large	no	Low	35.1	-7.8	0.69	no	-7.0	0.68	no
112	C	Large	no	Low	36.3	-8.1	0.63	yes	-8.0	0.72	no
113	C	Large	no	Low	36.8	-8.2	0.64	yes	-8.3	0.74	yes
114	C	Large	no	Low	36.2	-7.3	0.67	yes	-7.6	0.72	yes
115	C	Large	no	Low	38.0	-8.4	0.67	yes	-9.6	0.81	yes

Table A.1 - Driver Controlled Toyota 4Runner Fishhook Test Results - Maximum Corrected Lateral Acceleration and Roll Angle Values

Run Number	Driver	Tires	Outrigger Ballast	Fuel Level	Speed (mph)	1st Roll Peak after Steer Reversal			2nd Roll Peak after Steer Reversal		
						Roll Angle (deg)	Cor. Lat. Acc. (g)	Two-Wheel Lift	Roll Angle (deg)	Cor. Lat. Acc. (g)	Two-Wheel Lift
133	C	Large	yes	Low	31.5	8.4	-0.58	no	8.2	-0.66	no
134	C	Large	yes	Low	32.7	9.0	-0.58	no	8.9	-0.70	no
135	C	Large	yes	Low	33.6	9.7	-0.62	yes	9.6	-0.73	yes
136	C	Large	yes	Low	34.1	5.8	-0.58	no	6.8	-0.62	no
137	C	Large	yes	Low	33.9	10.3	-0.64	yes	9.3	-0.75	yes
138	C	Large	yes	Low	34.6	10.0	-0.66	yes	9.4	-0.75	yes
139	C	Large	yes	Low	34.4	4.9	-0.33	no	2.8	-0.24	no
140	C	Large	yes	Low	34.4	10.4	-0.65	yes	8.5	-0.73	yes
141	C	Large	yes	Low	32.4	-7.3	0.65	no	-7.5	0.67	no
142	C	Large	yes	Low	33.1	-7.3	0.70	no	-8.1	0.69	no
143	C	Large	yes	Low	33.6	-7.6	0.69	no	-8.2	0.67	no
144	C	Large	yes	Low	34.5	-7.6	0.69	no	-8.2	0.70	no
145	C	Large	yes	Low	36.0	-7.8	0.60	no	-9.0	0.75	yes
146	C	Large	yes	Low	36.1	-8.0	0.72	no	-8.7	0.73	yes
147	C	Large	yes	Low	37.0	-8.1	0.76	no	-9.0	0.77	yes
148	C	Large	yes	Low	36.7	-8.4	0.74	yes	-8.9	0.73	yes
149	C	Large	yes	Low	36.1	-7.7	0.72	no	-9.1	0.76	yes
216	C	Large	no	Full	34.5	10.2	-0.64	yes	9.3	-0.74	no
217	C	Large	no	Full	35.0	8.8	-0.62	no	8.7	-0.67	no
218	C	Large	no	Full	34.9	9.1	-0.64	no	9.7	-0.71	yes
219	C	Large	no	Full	35.9	10.3	-0.67	yes	10.7	-0.76	yes
220	C	Large	no	Full	36.7	10.7	-0.67	yes	9.2	-0.72	no
221	C	Large	no	Full	36.6	10.2	-0.66	yes	8.9	-0.72	no
222	C	Large	no	Full	37.4	11.5	-0.68	yes	8.2	-0.71	no

Table A.1 - Driver Controlled Toyota 4Runner Fishhook Test Results - Maximum Corrected Lateral Acceleration and Roll Angle Values

Run Number	Driver	Tires	Outrigger Ballast	Fuel Level	Speed (mph)	1st Roll Peak after Steer Reversal			2nd Roll Peak after Steer Reversal		
						Roll Angle (deg)	Cor. Lat. Acc. (g)	Two-Wheel Lift	Roll Angle (deg)	Cor. Lat. Acc. (g)	Two-Wheel Lift
223	C	Large	no	Full	34.6	-7.1	0.68	no	-7.4	0.68	no
224	C	Large	no	Full	34.7	-6.9	0.68	no	-7.3	0.67	no
225	C	Large	no	Full	36.1	-6.9	0.67	no	-7.3	0.69	no
226	C	Large	no	Full	37.0	-7.7	0.72	no	-8.2	0.73	no
227	C	Large	no	Full	36.9	-7.3	0.73	no	-7.6	0.72	no
228	C	Large	no	Full	37.5	-7.5	0.73	no	-8.3	0.75	no
229	C	Large	no	Full	38.2	-7.7	0.72	no	-7.7	0.77	no
230	C	Large	no	Full	39.2	-7.7	0.77	no	-10.0	0.77	yes
231	C	Large	no	Full	37.9	-7.7	0.73	no	-8.8	0.75	yes
234	A	Large	no	Full	33.1	-7.7	0.68	no	-8.2	0.67	no
235	A	Large	no	Full	34.4	-7.7	0.58	no	-8.6	0.71	no
236	A	Large	no	Full	35.3	-8.5	0.61	yes	-8.4	0.71	no
237	A	Large	no	Full	37.1	-8.9	0.64	yes	-9.1	0.77	yes
238	A	Large	no	Full	36.2	-8.8	0.64	yes	-10.0	0.77	yes
239	A	Large	no	Full	35.2	-8.7	0.64	yes	-10.0	0.79	yes
240	A	Large	no	Full	37.0	-9.2	0.67	yes	-10.0	0.80	yes
241	A	Large	no	Full	34.8	10.1	-0.63	yes	10.7	-0.82	yes
242	A	Large	no	Full	35.6	11.2	-0.65	yes	9.9	-0.81	yes
243	A	Large	no	Full	36.2	7.6	-0.77	yes	11.7	-0.69	yes
244	A	Large	no	Full	35.0	10.2	-0.65	yes	11.2	-0.82	yes
245	A	Large	no	Full	33.7	10.0	-0.65	yes	11.0	-0.80	yes
248	A	Small	no	Low	33.9	8.4	-0.64	no	8.5	-0.64	no

Table A.1 - Driver Controlled Toyota 4Runner Fishhook Test Results - Maximum Corrected Lateral Acceleration and Roll Angle Values

Run Number	Driver	Tires	Outrigger Ballast	Fuel Level	Speed (mph)	1st Roll Peak after Steer Reversal			2nd Roll Peak after Steer Reversal		
						Roll Angle (deg)	Cor. Lat. Acc. (g)	Two-Wheel Lift	Roll Angle (deg)	Cor. Lat. Acc. (g)	Two-Wheel Lift
249	A	Small	no	Low	34.5	10.5	-0.63	yes	10.4	-0.71	yes
250	A	Small	no	Low	34.0	10.4	-0.62	yes	11.0	-0.75	yes
251	A	Small	no	Low	33.3	8.9	-0.64	no	8.8	-0.64	no
252	A	Small	no	Low	32.4	9.5	-0.71	no	10.3	-0.74	yes
255	A	Small	no	Low	31.9	8.7	-0.62	yes	9.9	-0.68	yes
256	A	Small	no	Low	32.9	9.8	-0.69	yes	10.3	-0.70	yes
257	A	Small	no	Low	33.8	9.2	-0.69	yes	10.7	-0.69	yes
260	A	Small	no	Low	28.4	7.2	-0.63	no	7.9	-0.63	no
261	A	Small	no	Low	31.0	8.4	-0.69	no	8.8	-0.66	no
262	A	Small	no	Low	31.5	9.1	-0.69	no	8.7	-0.66	no
263	A	Small	no	Low	33.3	9.0	-0.67	yes	10.3	-0.76	yes
264	A	Small	no	Low	33.6	8.8	-0.65	yes	10.1	-0.74	yes
265	A	Small	no	Low	34.2	9.3	-0.67	yes	12.9	-0.79	yes
266	A	Small	no	Low	32.3	9.0	-0.65	yes	10.9	-0.78	yes
267	A	Small	no	Low	32.2	8.2	-0.64	no	8.7	-0.73	no
268	A	Small	no	Low	30.6	-7.7	0.67	no	-8.3	0.67	no
269	A	Small	no	Low	32.5	-7.8	0.67	no	-8.2	0.69	no
270	A	Small	no	Low	32.1	-7.5	0.66	no	-7.9	0.68	no
271	A	Small	no	Low	33.8	-8.3	0.68	no	-8.6	0.68	no
272	A	Small	no	Low	35.2	-9.1	0.65	no	-9.2	0.74	yes
273	A	Small	no	Low	34.1	-8.1	0.68	no	-8.3	0.69	no
274	A	Small	no	Low	33.4	-8.2	0.69	no	-8.3	0.68	no
275	A	Small	no	Low	34.1	-8.6	0.65	no	-9.8	0.74	yes

Table A.1 - Driver Controlled Toyota 4Runner Fishhook Test Results - Maximum Corrected Lateral Acceleration and Roll Angle Values

Run Number	Driver	Tires	Outrigger Ballast	Fuel Level	Speed (mph)	1st Roll Peak after Steer Reversal			2nd Roll Peak after Steer Reversal		
						Roll Angle (deg)	Cor. Lat. Acc. (g)	Two-Wheel Lift	Roll Angle (deg)	Cor. Lat. Acc. (g)	Two-Wheel Lift
278	A	Small	no	Low	30.3	-7.3	0.63	no	-8.0	0.64	no
279	A	Small	no	Low	32.0	-7.9	0.66	no	-8.3	0.66	no
280	A	Small	no	Low	33.8	-8.0	0.66	no	-8.6	0.67	no
281	A	Small	no	Low	34.6	-8.6	0.68	no	-8.9	0.67	no
282	A	Small	no	Low	35.8	-8.7	0.65	no	-8.9	0.69	no
283	A	Small	no	Low	37.0	-8.9	0.70	yes	-9.1	0.71	yes
284	A	Small	no	Low	36.6	-8.8	0.72	no	-9.7	0.73	yes
285	A	Small	no	Low	36.0	-8.4	0.70	no	-9.3	0.70	yes
286	A	Small	no	Low	33.4	8.3	-0.68	no	8.6	-0.66	no
287	A	Small	no	Low	35.3	9.2	-0.72	no	9.4	-0.73	no

Table A.2 - Driver Controlled Ford Bronco II Fishhook Test Results - Maximum Corrected Lateral Acceleration and Roll Angle Values

Test Number	Driver	Speed (mph)	Cor. Lat. Acc. (g)	Roll Angle (deg)	Two-Wheel Lift	Outrigger Ballast
3	A	27.4	0.57	-4.7	no	no
4	A	31.3	0.60	-5.8	no	no
5	A	32.5	0.65	-6.6	no	no
6	A	32.5	0.66	-6.8	no	no
7	A	36.5	0.71	-7.8	no	no
8	A	36.2	0.70	-7.5	no	no
9	A	37.8	0.74	-8.5	no	no
10	A	39.1	0.75	-8.5	no	no
11	A	39.4	0.76	-9.0	no	no
12	A	39.7	0.75	-8.6	no	no
13	A	39.1	0.80	-16.4	yes	no
14	A	35.2	-0.59	6.3	no	no
15	A	36.9	-0.61	6.5	no	no
16	A	38.0	-0.68	6.7	no	no
17	A	39.2	-0.67	6.8	no	no
19	A	39.8	-0.67	7.6	no	no
20	A	42.0	-0.72	9.5	yes	no
21	A	40.8	-0.69	7.7	no	no
22	A	41.6	-0.68	7.3	no	no
23	A	41.9	-0.68	7.4	no	no
25	A	42.1	-0.68	7.7	no	no
26	A	43.6	-0.71	10.0	yes	no
29	A	41.3	-0.68	6.6	no	no
30	A	40.1	-0.45	3.7	no	no
32	A	40.6	-0.71	7.2	no	no
33	A	42.7	-0.70	7.6	no	no
34	A	44.2	-0.71	8.3	no	no
35	A	44.6	-0.73	8.8	yes	no
37	A	45.8	-0.73	8.7	yes	no
39	A	48.6	-0.72	9.0	yes	no
40	A	49.0	-0.74	9.8	yes	no
41	A	48.4	-0.78	15.5	yes	no
42	A	45.6	-0.78	14.6	yes	no
43	A	38.4	0.72	-8.5	no	no
44	A	40.4	0.87	-16.2	yes	no
45	A	38.4	0.80	-17.2	yes	no
46	A	33.9	0.70	-7.6	no	no
47	A	36.0	0.72	-7.9	no	no
48	A	37.7	0.71	-8.7	no	no
49	A	38.2	0.72	-8.7	no	no
50	A	39.0	0.80	-17.7	yes	no

Table A.2 - Driver Controlled Ford Bronco II Fishhook Test Results - Maximum Corrected Lateral Acceleration and Roll Angle Values

Test Number	Driver	Speed (mph)	Cor. Lat. Acc. (g)	Roll Angle (deg)	Two-Wheel Lift	Outrigger Ballast
53	A	36.1	0.62	-7.4	no	yes
54	A	37.7	0.71	-7.3	no	yes
55	A	37.8	0.69	-7.6	no	yes
56	A	39.8	0.71	-7.8	no	yes
57	A	40.9	0.70	-8.1	no	yes
60	A	42.2	0.72	-8.5	no	yes
61	A	44.0	0.76	-9.3	yes	yes
62	A	44.3	0.74	-9.5	yes	yes
63	A	42.2	0.72	-8.6	no	yes
64	A	38.2	-0.66	8.2	no	yes
66	A	40.1	-0.66	8.4	no	yes
67	A	41.1	-0.65	8.4	no	yes
68	A	43.2	-0.66	8.8	no	yes
70	A	44.3	-0.68	8.8	no	yes
72	A	44.7	-0.71	9.3	yes	yes
73	A	42.1	-0.67	8.4	no	yes
74	A	44.4	-0.69	8.7	no	yes
75	A	43.5	-0.67	8.9	no	yes
76	A	45.6	-0.70	9.6	yes	yes
170	B	35.6	-0.60	7.6	no	no
172	B	36.2	-0.66	8.3	no	no
173	B	37.8	-0.68	7.7	no	no
174	B	39.1	-0.67	8.1	no	no
175	B	39.8	-0.75	7.8	no	no
176	B	40.5	-0.75	8.3	no	no
177	B	41.1	-0.65	9.4	no	no
178	B	42.3	-0.65	9.0	no	no
179	B	43.7	-0.65	9.0	no	no
180	B	43.0	-0.65	9.0	no	no
181	B	44.2	-0.66	9.8	yes	no
182	B	44.7	-0.66	10.7	no	no
183	B	45.2	-0.66	9.8	no	no
184	B	45.6	-0.71	11.1	yes	no
185	B	44.4	-0.68	10.5	yes	no
186	B	44.3	-0.64	8.6	no	no
189	B	38.5	0.74	-8.3	no	no
190	B	39.3	0.76	-9.5	yes	no
191	B	40.8	0.80	-18.5	yes	no
192	B	39.3	0.76	-9.2	yes	no
193	B	39.6	0.77	-8.7	yes	no
195	B	39.7	0.78	-19.7	yes	no

Table A.2 - Driver Controlled Ford Bronco II Fishhook Test Results - Maximum Corrected Lateral Acceleration and Roll Angle Values

Test Number	Driver	Speed (mph)	Cor. Lat. Acc. (g)	Roll Angle (deg)	Two-Wheel Lift	Outrigger Ballast
258	A	35.4	0.61	-6.5	no	no
259	A	37.7	0.65	-7.0	no	no
260	A	38.7	0.67	-7.5	no	no
261	A	40.5	0.73	-8.0	no	no
262	A	42.1	0.72	-7.6	no	no
263	A	42.9	0.73	-7.7	no	no
265	A	45.4	0.73	-7.8	no	no
267	A	46.7	0.77	-8.2	yes	no
268	A	46.6	0.76	-8.4	yes	no
269	A	42.2	-0.74	16.4	yes	no
270	A	40.2	-0.74	17.4	yes	no
271	A	38.0	-0.65	7.6	no	no
272	A	39.9	-0.68	8.1	no	no
273	A	40.4	-0.74	8.9	yes	no
274	A	41.2	-0.71	8.2	no	no
275	A	42.3	-0.75	18.8	yes	no
276	A	41.7	-0.76	19.2	yes	no
347	C	35.6	0.59	-3.9	no	no
348	C	34.6	0.62	-6.0	no	no
349	C	39.8	0.64	-6.4	no	no
350	C	42.2	0.68	-6.9	no	no
351	C	43.4	0.70	-7.0	no	no
352	C	45.2	0.82	-7.0	no	no
353	C	46.3	0.72	-8.1	no	no
354	C	47.3	0.71	-7.2	no	no
355	C	47.9	0.71	-7.4	no	no
356	C	41.8	-0.64	6.3	no	no
357	C	43.0	-0.72	8.2	no	no
358	C	45.1	-0.73	9.4	no	no
359	C	46.2	-0.75	9.5	yes	no
360	C	47.1	-0.73	8.7	no	no
361	C	46.9	-0.74	9.4	yes	no
362	C	47.7	-0.78	8.2	no	no
363	C	46.4	-0.72	8.3	no	no

Appendix B: Fishhook Steering Profile Studies

Individual Test Results

Table B.1 - Individual Test Results for Fishhook Steering Profile Study Number 1

Steer Direction	First Steer Angle (deg)	Run Number	Speed (mph)	Cor. Lateral Acc. (g)		Roll Angle (deg)		Roll Rate (deg/sec)		Yaw Rate (deg/sec)		Two-Wheel Lift
				1st Steer	2nd Steer	1st Steer	2nd Steer	1st Steer	2nd Steer	1st Steer	2nd Steer	
Left-Right	270	5	7.9	-0.19	0.30	1.8	-2.9	4.8	-4.7	-16.7	37.4	no
Left-Right	270	7	10.5	-0.27	0.45	2.7	-4.7	6.5	-6.5	-21.3	48.4	no
Left-Right	270	8	13.0	-0.38	0.61	3.8	-5.8	8.5	-10.1	-26.5	48.4	no
Left-Right	270	9	16.0	-0.42	0.63	4.3	-6.1	9.1	-11.3	-28.4	48.4	no
Left-Right	270	10	19.1	-0.58	0.68	5.0	-6.5	11.9	-17.3	-32.1	48.4	no
Left-Right	270	11	20.7	-0.59	0.69	5.0	-6.5	12.3	-19.6	-32.1	48.4	no
Left-Right	270	12	21.2	-0.60	0.70	5.4	-6.6	12.6	-19.4	-32.3	48.4	no
Left-Right	270	13	23.0	-0.61	0.69	5.5	-6.6	12.9	-21.1	-31.8	48.4	no
Left-Right	270	14	23.6	-0.64	0.71	5.7	-6.8	13.4	-24.3	-31.8	48.4	no
Left-Right	270	15	24.7	-0.67	0.73	5.7	-6.5	14.7	-26.2	-31.0	48.4	no
Left-Right	270	16	26.7	-0.68	0.72	5.8	-7.0	14.8	-28.0	-31.3	48.4	no
Left-Right	270	17	28.5	-0.70	0.73	5.9	-7.2	15.8	-30.6	-30.9	48.4	no
Left-Right	270	18	29.6	-0.71	0.75	6.1	-7.2	15.6	-32.9	-30.0	48.4	no
Left-Right	270	19	29.9	-0.71	0.76	6.0	-7.6	16.7	-33.2	-29.3	48.4	no
Left-Right	270	20	31.6	-0.71	0.77	6.2	-7.9	17.2	-35.1	-29.0	48.4	no
Left-Right	270	21	33.6	-0.73	0.79	6.4	-7.6	17.9	-38.0	-27.8	48.1	no
Left-Right	270	22	34.3	-0.74	0.79	6.5	-7.9	18.4	-39.3	-27.6	46.1	no
Left-Right	270	23	35.8	-0.77	0.82	6.4	-8.8	18.5	-39.9	-29.4	45.3	no
Left-Right	270	24	37.0	-0.75	0.81	6.3	-8.8	17.6	-40.9	-28.4	45.3	no
Left-Right	270	25	33.2	-0.72	0.79	6.2	-7.4	18.4	-35.6	-27.4	45.6	no
Left-Right	270	26	35.4	-0.73	0.81	6.4	-7.9	18.2	-37.4	-27.4	48.4	no
Left-Right	270	27	36.4	-0.77	0.83	6.4	-8.5	19.4	-41.1	-28.6	46.0	no
Left-Right	270	28	37.9	-0.75	0.87	6.5	-9.0	19.1	-41.8	-27.0	44.1	yes
Left-Right	270	29	39.3	-0.74	0.87	6.6	-9.5	18.9	-42.2	-27.0	46.0	yes
Left-Right	270	30	40.3	-0.78	0.95	6.6	-9.6	20.1	-44.8	-28.0	48.6	yes
Right-Left	270	31	23.4	0.64	-0.71	-5.7	6.7	-13.8	22.2	31.1	-52.7	no
Right-Left	270	32	31.2	0.71	-0.74	-6.2	7.5	-17.2	32.4	31.1	-50.8	no
Right-Left	270	33	32.0	0.73	-0.76	-6.2	7.8	-17.6	36.1	30.8	-46.7	no
Right-Left	270	34	35.3	0.75	-0.87	-6.4	8.8	-17.2	38.3	31.7	-52.3	no
Right-Left	270	35	35.8	0.75	-0.85	-6.4	8.9	-17.8	40.9	30.8	-42.7	no
Right-Left	270	36	37.6	0.76	-0.97	-6.6	9.9	-19.2	41.3	31.2	-51.7	yes
Right-Left	270	37	37.0	0.75	-0.91	-6.6	9.2	-19.3	42.2	29.9	-47.3	yes
Right-Left	270	38	38.7	0.76	-0.97	-6.6	9.7	-18.0	39.6	31.4	-50.0	yes
Right-Left	270	39	39.3	0.77	-0.98	-6.6	10.0	-20.1	43.5	29.8	-52.8	yes

Table B.1 - Individual Test Results for Fishhook Steering Profile Study Number 1

Steer Direction	First Steer Angle (deg)	Run Number	Speed (mph)	Cor. Lateral Acc. (g)		Roll Angle (deg)		Roll Rate (deg/sec)		Yaw Rate (deg/sec)		Two-Wheel Lift
				1st Steer	2nd Steer	1st Steer	2nd Steer	1st Steer	2nd Steer	1st Steer	2nd Steer	
Right-Left	180	41	20.4	0.48	-0.69	-4.6	6.6	-12.9	16.7	23.3	-52.3	no
Right-Left	180	42	30.4	0.67	-0.73	-5.9	6.9	-17.9	30.3	26.6	-48.7	no
Right-Left	180	43	32.1	0.69	-0.78	-6.2	7.4	-17.8	34.1	26.8	-44.2	no
Right-Left	180	44	34.1	0.71	-0.80	-6.2	7.9	-19.6	37.6	26.2	-44.3	no
Right-Left	180	45	36.7	0.72	-0.88	-6.4	8.8	-20.6	40.9	26.4	-43.0	no
Right-Left	180	46	37.4	0.73	-0.84	-6.4	8.5	-20.8	40.5	26.3	-40.8	no
Right-Left	180	47	38.4	0.74	-0.93	-6.4	9.3	-20.9	42.3	26.5	-45.2	yes
Right-Left	180	48	39.6	0.74	-0.89	-6.8	11.3	-21.5	45.9	26.2	-45.4	yes
Right-Left	180	49	39.4	0.72	-0.93	-6.5	9.2	-20.2	39.5	26.7	-48.7	yes
Right-Left	180	50	39.7	0.76	-0.88	-6.9	8.9	-20.5	42.1	28.8	-52.4	yes
Left-Right	180	51	20.7	-0.44	0.70	4.2	-6.8	13.1	-15.6	-21.1	48.8	no
Left-Right	180	52	30.4	-0.63	0.76	5.5	-7.2	17.8	-29.7	-23.3	48.8	no
Left-Right	180	53	32.9	-0.66	0.75	5.6	-7.7	17.5	-31.8	-23.9	48.8	no
Left-Right	180	54	34.3	-0.67	0.77	5.6	-7.8	18.0	-32.4	-23.0	46.3	no
Left-Right	180	55	36.2	-0.68	0.82	5.8	-7.9	18.6	-35.8	-23.3	46.9	no
Left-Right	180	56	37.6	-0.70	0.81	6.0	-8.7	19.2	-37.1	-23.9	47.2	no
Left-Right	180	57	38.3	-0.71	0.81	6.0	-8.6	19.5	-38.8	-23.4	43.6	no
Left-Right	180	58	40.9	-0.72	0.88	6.1	-9.8	19.1	-40.0	-25.1	46.6	yes
Left-Right	180	59	40.6	-0.72	0.86	6.2	-9.3	21.4	-41.9	-23.2	47.1	yes
Left-Right	180	60	41.3	-0.72	0.88	6.0	-10.6	20.5	-41.5	-23.2	44.3	yes

Table B.2 - Individual Test Results for Fishhook Steering Profile Study Number 2

Program Number	Pause Duration	Steer Rate (deg/sec)	Run Number	Speed (mph)	Cor. Lateral Acc. (g)		Roll Angle (deg)		Roll Rate (deg/sec)		Yaw Rate (deg/sec)	
					1st Steer	2nd Steer	1st Steer	2nd Steer	1st Steer	2nd Steer	1st Steer	2nd Steer
0	0	500	258	30.3	0.63	-0.78	-6.2	7.3	-16.3	28.5	29.4	-49.5
0	0	500	264	30.3	0.64	-0.80	-6.3	7.0	-16.0	29.5	29.5	-49.3
0	0	500	109	30.6	0.65	-0.80	-6.3	7.8	-16.6	28.9	30.1	-50.6
0	0	500	111	30.7	0.66	-0.81	-6.4	7.7	-16.8	29.5	29.9	-49.8
			Avg	30.5	0.65	-0.80	-6.3	7.5	-16.4	29.1	29.7	-49.8
1	0	750	259	30.3	0.57	-0.84	-6.4	7.9	-22.0	36.3	29.5	-49.2
1	0	750	267	29.9	0.56	-0.82	-6.1	8.3	-22.0	34.8	30.5	-49.7
1	0	750	105	30.4	0.59	-0.90	-6.8	9.2	-22.6	35.9	31.7	-50.6
1	0	750	113	30.4	0.58	-0.86	-6.3	8.4	-21.8	36.2	31.1	-49.7
			Avg	30.3	0.58	-0.86	-6.4	8.4	-22.1	35.8	30.7	-49.8
2	0.25	500	261	30.8								
2	0.25	500	265	30.1								
2	0.25	500	104	30.7								
2	0.25	500	110	30.3								
			Avg	30.5								
3	0.25	750	260	30.2	0.69	-0.82	-6.5	8.0	-22.5	37.4	31.5	-49.2
3	0.25	750	270	30.3	0.70	-0.83	-6.6	8.2	-22.2	36.9	32.2	-49.4
3	0.25	750	107	30.8	0.71	-0.87	-6.5	8.2	-22.6	36.9	31.7	-49.7
3	0.25	750	116	30.4	0.71	-0.85	-6.5	8.7	-22.5	38.8	32.2	-49.5
			Avg	30.4	0.70	-0.84	-6.5	8.3	-22.4	37.5	31.9	-49.4
4	0.5	500	256	30.5	0.72	-0.78	-6.7	7.2	-17.1	26.2	30.2	-50.1
4	0.5	500	269	30.2	0.72	-0.79	-6.5	7.4	-16.4	26.5	31.6	-49.7
4	0.5	500	108	30.6	0.74	-0.81	-6.7	7.9	-17.3	27.7	31.4	-50.2
4	0.5	500	114	30.1	0.72	-0.79	-6.7	7.6	-16.7	26.3	32.2	-49.5
			Avg	30.3	0.73	-0.79	-6.7	7.5	-16.9	26.7	31.3	-49.9

Table B.2 - Individual Test Results for Fishhook Steering Profile Study Number 2

Program Number	Pause Duration	Steer Rate (deg/sec)	Run Number	Speed (mph)	Cor. Lateral Acc. (g)		Roll Angle (deg)		Roll Rate (deg/sec)		Yaw Rate (deg/sec)	
					1st Steer	2nd Steer	1st Steer	2nd Steer	1st Steer	2nd Steer	1st Steer	2nd Steer
5	0.5	750	262	30.4	0.75	-0.84	-6.5	8.3	-22.5	35.8	32.2	-49.6
5	0.5	750	268	30.1	0.74	-0.81	-6.5	7.9	-22.0	36.3	32.6	-49.8
5	0.5	750	106	30.4	0.73	-0.84	-6.8	8.4	-22.5	37.5	32.7	-50.7
5	0.5	750	117	30.5	0.73	-0.82	-6.8	7.8	-22.2	36.8	32.3	-49.4
			Avg	30.3	0.74	-0.83	-6.7	8.1	-22.3	36.6	32.5	-49.9
6	1	500	263	30.0	0.72	-0.77	-6.6	7.0	-16.9	22.3	30.8	-50.0
6	1	500	271	29.9	0.72	-0.79	-6.7	7.4	-16.6	22.6	31.1	-49.6
6	1	500	103	30.3	0.74	-0.79	-6.9	7.6	-17.6	23.6	31.8	-50.4
6	1	500	115	30.4	0.74	-0.80	-6.7	7.5	-16.4	21.2	31.9	-49.4
			Avg	30.2	0.73	-0.79	-6.7	7.4	-16.9	22.4	31.4	-49.8
7	1	750	257	30.1	0.73	-0.78	-6.5	7.1	-21.4	32.1	32.1	-50.0
7	1	750	266	30.3	0.74	-0.79	-6.9	7.8	-22.6	33.5	31.9	-49.7
7	1	750	102	30.8	0.76	-0.81	-6.7	7.8	-22.7	33.3	31.9	-50.4
7	1	750	112	30.2	0.76	-0.80	-6.9	7.8	-22.0	32.9	32.5	-50.0
			Avg	30.3	0.75	-0.80	-6.8	7.6	-22.2	33.0	32.1	-50.0

Appendix C: Descriptive Text for Graphical Images

Figure: 6.1: Pulse Steer Handwheel Input

This figure represents the shape of the pulse steer handwheel input. The y-axis is labeled Handwheel Angle and the x-axis is labeled Time.

The handwheel angle trace is basically a triangle. The handwheel angle starts at 0 degrees, increases to 80 degrees in 0.1 seconds and decreases back to 0 in another 0.1 seconds. In other words, the triangle has a base equal to 0.2 seconds and a height of 80 degrees.

Figure 6.2: Handwheel Steering Input for the Sinusoidal Sweep Maneuver.

This figure represents the shape of the handwheel input for the sinusoidal sweep maneuver. The y-axis is labeled Handwheel Angle in degrees and ranges from -100 to +100 degrees in 20-degree increments. The x-axis is labeled as Time in seconds and ranges from 0 to 25 seconds in 5-second increments.

As the maneuver name implies, the handwheel input is a swept sine that starts at a low frequency (longer duration), increases to a high frequency (shorter duration), and then returns to a low frequency. The amplitude of the sinusoidal peaks is 80 degrees. There are a total of 15 negative peaks and 14 positive peaks, with the first sinusoid starting at 3 seconds and in a negative direction. The last sinusoid ends at 21 seconds.

Figure 6.3: Handwheel Steering Input for the Resonant Steer Maneuver

This figure represents the shape of the handwheel input for the resonant steer maneuver. The y-axis is labeled Handwheel Angle in degrees ranging from –150 to +150 degrees in 50 degree increments. The x-axis is labeled Time in seconds ranging from 0 to 25 seconds in 5 second increments.

This is a series of 10 complete sine waves all of equal amplitude (110 degrees) and frequency (0.5 Hertz). The first sine wave starts negative at approximately 4 seconds and the last sine wave ends at approximately 24 seconds.

Figure 7.1: Vehicle Speed and Roll Angle for 4 Runner J-Turn Test Number 130

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Vehicle Speed in mph and Roll Angle in degrees. The top pane has a range of 0 to 50 mph in 10 mph increments and the bottom pane has a range of –15 to +5 degrees in 5-degree increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 8 seconds in 1-second increments.

The upper pane has a single trace that represents the measured Vehicle Speed for Test 130. The trace begins towards the top of the y-axis at approximately 47 mph and remains relatively flat for the first one second. It then begins a gentle descent down to approximately 17 mph at 6 seconds where the line again remains relatively flat out to 8 seconds.

The lower pane has a single trace that represents the measured Roll Angle for Test 130. The trace begins slightly above the zero reference line and remains relatively flat until approximately 0.8 second. The trace then falls sharply to –7 degrees at 1 second and oscillates between –6 to –8 degrees across the time period from 1 to 4 seconds. The trace then dips down to –14 degrees at 5 seconds and returns to approximately –2.5 degrees at 6 seconds. This is followed by some minor oscillations until 8 seconds where the trace ends.

Figure 7.2: Handwheel Angle and Vehicle Speed Traces for Two Similar Vehicle Speed Trace Tests – Driver A

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Handwheel Angle in degrees and Vehicle Speed in mph. The top pane has a range of –350 to +50 degrees in 50-degree increments and the bottom pane has a range of 20 to 45 mph in 5 mph increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 6 seconds in 1-second increments.

The upper pane has two traces that represent the measured Handwheel Angle for Tests 121 and 122. Driver A conducted both of these tests. Both traces start near the origin and remain flat until approximately 0.5 second. The traces then fall sharply to –330 degrees at 1 second. The traces remain flat at this level until approximately 4 seconds where they both start to return to zero. The return to zero represents the completion of the test.

The lower pane also has two traces that represent the measured Vehicle Speed for Tests 121 and 122. The two traces are nearly identical throughout the test and both begin at approximately 40 mph and remain relatively flat until the one second mark, where they start to fall off gradually. By 2 seconds, the vehicle speed is 35 mph, 3 seconds - 29 mph, 4 seconds - 26 mph, and 6 seconds - 23 mph.

Figure 7.3: Corrected Lateral Acceleration and Roll Angle Traces for Two Similar Vehicle Speed Trace Tests – Driver A

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Corrected Lateral Acceleration in g's and Roll Angle in degrees. The top pane has a range of –0.8 to 0 g in 0.1-g increments and the bottom pane has a range of 0 to 10 degrees in 2-degree increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 6 seconds in 1-second increments.

The upper pane has two traces that represent the Corrected Lateral Acceleration for Tests 121 and 122. Driver A conducted both of these tests. Both traces start near the origin and remain flat until approximately 0.5 second. The traces then fall sharply to approximately –0.65 g at 1 second. For both traces, the response following this initial negative peak is oscillatory with negative peaks ranging from approximately –0.6 to –0.78 g. The largest negative peak occurs on the fourth oscillation for both tests. The oscillation frequency for both tests is very similar, but the two traces are slightly out of phase.

The lower pane also has two traces that represent the Roll Angle for Tests 121 and 122. Both traces start near the origin and remain flat until approximately 0.5 seconds and then increase sharply to approximately 7 degrees near 1.1 seconds. As was the case in the upper pane, the two traces have an oscillatory response that are very similar in shape and frequency of oscillation, but are slightly out of phase with each other. The peak values occur on the fourth oscillation for both tests and are approximately 8.3 degrees for both tests.

Figure 7.4: Handwheel Angle and Vehicle Speed Traces for Two Dissimilar Vehicle Speed Trace Tests – Driver A.

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Handwheel Angle in degrees and Vehicle Speed in mph. The top pane has a range of –350 to +50 degrees in 50-degree increments and the bottom pane has a range of 20 to 45 mph in 5-mph increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 6 seconds in 1-second increments.

The upper pane has two traces that represent the measured Handwheel Angle for Tests 121 and 123. Driver A conducted both of these tests. Both traces start near the origin and remain flat until approximately 0.5 second. The traces then fall sharply to –330 degrees at 1 second. The trace for Test 123 starts turning a little bit earlier than Test 121, but both tests reach –330 degrees at approximately the same time. The traces remain flat at this level until approximately 4 seconds where Test 121 starts to return to zero. Test 123 doesn't start to return to zero until approximately 5.5 seconds. The return to zero represents the completion of the test.

The lower pane also has two traces that represent the measured Vehicle Speed for tests 121 and 123. The two traces are nearly identical throughout the test and both begin at approximately 40 mph and remain relatively flat until the one second mark, where they both start to fall off gradually. The two tests start diverging at about 1.75 seconds, with Test 123 maintaining a higher speed than Test 121. By 2 seconds, the vehicle speed is 35 mph for Test 121 and 36 mph for Test 123. Continuing to list Test 121 first, at 3 seconds - 29 and 34 mph, at 4 seconds - 26 and 32 mph, at 5 seconds 24 and 28 mph, and at 6 seconds - 23 and 25 mph.

Figure 7.5: Corrected Lateral Acceleration and Roll Angle Traces for Two Dissimilar Vehicle Trace Tests – Driver A

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Corrected Lateral Acceleration in g's and Roll Angle in degrees. The top pane has a range of –0.8 to 0 g in 0.1-g increments and the bottom pane has a range of 0 to 10 degrees in 2-degree increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 6 seconds in 1-second increments.

The upper pane has two traces that represent the Corrected Lateral Acceleration for Tests 121 and 123. Driver A conducted both of these tests. Both traces start near the origin and remain flat until approximately 0.5 second. The traces then fall sharply to approximately –0.65 g at 1 second. For both traces, the response following this initial negative peak is oscillatory with negative peaks ranging from approximately –0.6 to –0.78 g. The largest negative peak occurs on the fourth oscillation for Test 121 (-0.78 g) and the third oscillation for Test 123 (-0.70 g). The oscillation frequency for both tests is very similar for the two traces, but after the third oscillation, the oscillations for Test 123 have a lower magnitude.

The lower pane also has two traces that represent the Roll Angle for Tests 121 and 123. Both traces start near the origin and remain flat until approximately 0.5 seconds and then increase sharply to approximately 7 degrees near 1.1 seconds. As was the case in the upper pane, the two traces have an oscillatory response that are very similar in shape and frequency of oscillation. The largest peak occurs on the fourth oscillation for Test 121 (8.3 degrees) and the third oscillation for Test 123 (7.9 degrees). After the third oscillation, the oscillations for Test 123 have a lower magnitude.

Figure 7.6: Handwheel Angle and Vehicle Speed Traces for Tests with Greater Throttle Input – Driver C

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Handwheel Angle in degrees and Vehicle Speed in mph. The top pane has a range of –350 to +50 degrees in 50-degree increments and the bottom pane has a range of 20 to 45 mph in 5-mph increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 6 seconds in 1-second increments.

The upper pane has two traces that represent the measured Handwheel Angle for Tests 179 and 180. Driver C conducted both of these tests. Both traces start near the origin and remain flat until approximately 0.7 second. The traces then fall sharply to –330 degrees at 1.2 seconds. The traces remain flat at this level until the end of the trace (6 seconds).

The lower pane also has two traces that represent the measured Vehicle Speed for Tests 179 and 180. The trace for Test 179 starts near 40 mph and the trace for Test 180 starts near 41.5 mph. Both traces remain relatively flat until the 1.2 seconds mark, where they start to fall off gradually. They fall off much less gradually than those for Tests 121 and 122 shown in Figure 7.2. At 4 seconds, Test 179 has dropped to approximately 31 mph and Test 180 has dropped to 35 mph. Tests 121 and 122 also started near 40 mph, but had dropped to 26 mph by 4 seconds.

Figure 7.7: Corrected Lateral Acceleration and Roll Angle Traces for Tests with Greater Throttle Input – Driver C

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Corrected Lateral Acceleration in g's and Roll Angle in degrees. The top pane has a range of –0.8 to 0 g in 0.1-g increments and the bottom pane has a range of 0 to 10 degrees in 2-degree increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 6 seconds in 1-second increments.

The upper pane has two traces that represent the Corrected Lateral Acceleration for Tests 179 and 180. Driver C conducted both of these tests. Both traces start near the origin and remain flat until approximately 0.7 second. The traces then fall sharply to approximately –0.62 g at 1.2 seconds. For both traces, the response following this initial negative peak are much less oscillatory than those seen for Tests 121 and 122 in Figure 7.2. The maximum negative peak value for both traces is approximately –0.67 g at 1.7 seconds.

The lower pane also has two traces that represent the Roll Angle for Tests 179 and 180. Both traces start near the origin and remain flat until approximately 0.7 seconds and then increase sharply to approximately 6.5 degrees near 1.1 seconds. As was the case in the upper pane, for both traces, the response following this initial peak are much less oscillatory than those seen for Tests 121 and 122 in Figure 7.2. The maximum peak value for both traces is approximately 7 degrees.

Figure 7.8: Handwheel Angle and Vehicle Speed Traces for Two Dissimilar Vehicle Speed Trace Tests – Driver A and C

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Handwheel Angle in degrees and Vehicle Speed in mph. The top pane has a range of –350 to +50 degrees in 50-degree increments and the bottom pane has a range of 20 to 45 mph in 5-mph increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 6 seconds in 1-second increments.

The upper pane has two traces that represent the measured Handwheel Angle for Test 121 conducted by Driver A and Test 180 conducted by Driver C. These traces were previously described in Figures 7.2 and 7.6 respectively. Both traces start near the origin and remain flat until approximately 0.7 second. The traces then fall sharply to –330 degrees at 1.1 seconds. Test 180 remains flat at this level until the end of the trace (6 seconds), while Test 121 start to return to zero slightly after 4 seconds.

The lower pane also has two traces that represent the measured Vehicle Speed for Tests 121 and 180. The trace for Test 121 starts near 40 mph and the trace for Test 180 starts near 41.5 mph. Both traces remain relatively flat until the 1.2 seconds mark, where they start to fall off gradually. Test 121 falls off more rapidly than Test 180. At 4 seconds, Test 121 has dropped to approximately 26 mph and Test 180 has dropped to only 35 mph.

Figure 7.9: Corrected Lateral Acceleration and Roll Angle Traces for Two Dissimilar Vehicle Trace Tests – Drivers A and C

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Corrected Lateral Acceleration in g's and Roll Angle in degrees. The top pane has a range of –0.8 to 0 g in 0.1-g increments and the bottom pane has a range of 0 to 10 degrees in 2-degree increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 6 seconds in 1-second increments.

The upper pane has two traces that represent the Corrected Lateral Acceleration for Test 121 conducted by Driver A and Test 180 conducted by Driver C. Both traces start near the origin and remain flat until approximately 0.7 second. The traces then fall sharply to approximately –0.62 g at 1.2 seconds. The response for Test 121 is much more oscillatory than Test 180 following this initial negative peak. The maximum negative peak value for Test 121 is approximately –0.78 g at 2.7 seconds. For Test 180, the maximum negative peak value is –0.67 g at 1.7 seconds.

The lower pane also has two traces that represent the Roll Angle for Tests 121 and 180. Both traces start near the origin and remain flat until approximately 0.7 seconds and then increase sharply to approximately 7 degrees for Test 121 and 6.5 degrees for Test 180. As was the case in the upper pane, the response following this initial peak for Test 180 is much less oscillatory than that for Test 121. The maximum peak value for Test 121 and 180 are approximately 8.3 and 7 degrees respectively.

Figure 7.10: Handwheel Angle Versus Time for Bronco II Test No. 280

The y-axis is labeled Handwheel Angle in degrees and has a range of 0 to 350 degrees in 50-degree increments. The x-axis is labeled Time in seconds and has a range of 0 to 5 seconds in 1-second increments.

The single trace begins near the origin and remains flat for approximately 0.2 second, then rises sharply to 320 degrees near 0.7 second. The trace stays flat at this level until approximately 3.5 seconds where a slight positive bump occurs. The test is considered to be over at this point. The line begins to fall at 3.7 seconds from 325 degrees to 250 degrees at 4 seconds, then down to 80 degrees at 4.8 seconds. The line then ascends slightly to 100 degrees at 5 seconds.

Figure 7.11: Handwheel Rate Versus Time for Bronco II Test No. 280

The y-axis is labeled Handwheel Rate in degrees per second and has a range of -500 to +1000 degrees in 500-degrees per second increments. The x-axis is labeled Time in seconds and has a range of 0 to 5 seconds in 1-second increments.

The single trace begins near the origin and rises sharply to about 800 degrees/second at the apex near 0.4 seconds, then falls just rapidly back to zero near 0.8 seconds. The trace slightly overshoots the y-axis in the negative direction, but then returns back to the y-axis where it remains flat until 3.3 seconds. This corresponds to the +320 degree handwheel angle shown in Figure 7.10. As the handwheel angle is returned towards zero, the handwheel rate trace dips down to –250 degrees/second at 4 seconds, blips back up to –200 degrees/second at 4.2 seconds, then falls back down to –400 degrees/second at 4.5 seconds. The trace rises back up to approximately 75 degrees/second at 5 seconds.

Figure 7.12: Pedal Force Versus Time for Bronco II test No. 280.

The y-axis is labeled Pedal Force in units of pounds-force and has a range of -20 to +100 pounds-force in 20-pounds-force increments. The x-axis is labeled Time in seconds and has a range of 0 to 5 seconds in 1-second increments.

The trace starts at the origin and remains flat until 1.4 seconds where the brake pulse begins. The trace quickly climbs to a 100 pounds-force peak value at 1.6 seconds and then falls quickly back to zero by 1.8 seconds. There is one minor, short duration peak immediately after this one with a 10 pounds-force magnitude at 1.9 seconds. The trace is then flat from 2.1 seconds to the end of the timeline at 5 seconds.

Figure 7.13: Longitudinal Acceleration Versus Time for Bronco II Test 280.

The y-axis is labeled Longitudinal Acceleration in g's and has a range of -0.5 to +0.2 g in 0.1-g increments. The x-axis is labeled Time in seconds and has a range of 0 to 5 seconds in 1-second increments.

The trace begins at 0 seconds and 0.05 g. The line dips slightly and returns to 0.05 g by 0.3 seconds, where it then falls rapidly down to -0.17 g at 0.4 seconds. With some oscillation, the trace returns to -0.1 g at 1.5 seconds. This part of the trace is labeled "Longitudinal Acceleration due to Handwheel Input." The trace then falls quickly to a low of -0.45 g at 1.8 seconds, then rises quickly back up to -0.08 g's at 2.3 seconds. The negative peak at 1.8 seconds is labeled "Peak Longitudinal Acceleration due to Pulse Brake". The trace then slowly returns toward the x-axis with some minor oscillations.

Figure 7.14: Roll Angle Versus Time for Bronco II test No. 280.

The y-axis is labeled Roll Angle in degrees and has a range of –8 to +1 in 1-degree increments. The x-axis is labeled Time in seconds and has a range of 0 to 5 seconds in 1-second increments.

The trace begins slightly above the origin near 0.2 degrees and remains at this level until approximately 0.3 seconds where it falls to –5 degrees at 0.75 seconds. The trace rises slightly to a small peak of –4.5 degrees at 1 second. The trace then falls to –5.7 degrees at 1.25 seconds. This point is labeled "Peak Roll Angle Pre-Pulse." The trace then ascends to a peak of –2.8 degrees near 1.8 seconds. This point is labeled "Dip in Roll Angle Caused by Pulse." The trace then falls to a low of -7.2 degrees at 2.3 seconds. This point is labeled "Peak Roll Angle Post Pulse." The trace slowly returns toward the x-axis with some minor oscillations.

Figure 7.15: Corrected Lateral Acceleration Versus Time for Bronco II test No. 280.

The y-axis is labeled Corrected Lateral Acceleration in g's from –0.1 to +0.9 g in 0.1-g increments. The x-axis is labeled Time in seconds and has a range of 0 to 5 seconds in 1-second increments.

The trace begins at the origin and remains flat until 0.2 seconds before climbing to a series of 3 major peaks. The first peak is 0.73 g at 1.2 seconds and is labeled "Peak Lateral Acceleration Pre-Pulse." The trace then falls to 0.5 g at 1.7 seconds and this point is labeled "Dip in Lateral Acceleration Due to

Pulse". The trace rises to the second peak of 0.8 g at 1.9 seconds and is labeled "Peak Lateral Acceleration Post-Pulse." There is another dip down to 0.53 g followed by the final major peak of 0.78 g at 2.7 seconds. The trace then lowers to 0.6 g at 2.8 seconds and remains fairly flat and centered around 0.6 g until 4.2 seconds where the trace returns towards the x-axis.

Figure 7.16: Roll Rate Versus Time for Bronco II test No. 280.

The y-axis is labeled Roll Rate in degrees/second from –30 to +10 degrees/second in 5-degree/second increments. The x-axis is labeled Time in seconds and has a range of 0 to 5 seconds in 1-second increments.

The single trace starts near the origin then quickly falls down to a negative peak of -18 degrees/second at 0.5 seconds. This low spot is labeled "Peak Roll Rate Pre-Pulse." The trace then ascends to –2 degree/second at 0.8 seconds, falls to -10 degree/second at 1.1 second, rises to another small peak at -2 degrees/second at 1.3 seconds, and then falls to -5 degrees/second at 1.5 seconds. The trace then reaches a larger peak of 9 degree/second at 1.7 seconds. This point is labeled "Dip in Roll Rate Due to Pulse." The trace then drops rapidly to -26 degrees/second at 2 seconds and this point is labeled "Peak Roll Rate Post-Pulse." The trace then goes through several oscillations. These peaks and troughs in order of appearance are 4 degree/second at 2.4 seconds; 6 degrees/second at 2.9 seconds; -3 degrees/second at 3.3 seconds; -3 degrees/second at 3.8 seconds; and 5 degrees/second at 4.6 seconds.

Figure 7.17: Yaw Rate Versus Time for Bronco II test No. 280.

The y-axis is labeled Yaw Rate in degrees/second from –5 to +40 degrees/second in 5-degrees/second increments. The x-axis is labeled Time in seconds and has a range of 0 to 5 seconds in 1-second increments.

The trace begins at the origin and remains flat until 0.3 seconds. The trace then climbs sharply to a max at of 32 degrees/second at 0.8 seconds, where the peak is labeled "Peak Yaw Rate Pre-Pulse." The trace then falls slightly and rises again to 31 degrees/second at 1.3 seconds. The trace then dips down to 22 degrees/second at 1.8 seconds and this point is labeled "Dip in Yaw Rate Due to Pulse." Following this dip, the trace rises to 28 degrees/second at 2.3 seconds, falls to 15 degrees/second at 2.6 seconds, and rises very gradually to the next peak at 37 degrees/second at 3.6 seconds. This last peak is labeled "Peak Yaw Rate Post-Pulse." Following this peak, the trace descends toward the x-axis.

Figure 7.18: J-Turn with Pulse Brake Driver Comparison - Handwheel Angle and Brake Pedal Force

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Handwheel Angle in degrees and Brake Pedal Force in pounds-force. The top pane has a range of –400 to 0 degrees in 50-degree increments and the bottom pane has a range of -50 to 250 pounds-force in 50-pounds-force increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 4 seconds in 0.5-second increments.

The upper pane has two traces that represent the measured Handwheel Angle for Test 289 conducted by Driver A and Test 336 conducted by Driver C. Both traces start near the origin and drop sharply to –330 degrees at 0.6 second. Both tests remain flat at this level until the end of the trace (4 seconds). The two traces are nearly indistinguishable.

The lower pane also has two traces that represent the Brake Pedal Force for Tests 229 and 336 (Drivers A and C respectively). Both traces start near the origin and remain flat until the brake application is made. They return to zero and stay flat after the brake application. The brake application for Test 289 starts at 1.25 seconds and is 0.5 second in duration. The apex is located near 1.5 seconds and has a 125 pounds-force magnitude. The brake application for Test 336 begins near 0.9 seconds and is 0.5 seconds in duration. The apex is relatively flat from 1.05 to 1.2 seconds and has a 200 pounds-force magnitude.

Figure 7.19: J-Turn with Pulse Brake Driver Comparison – Longitudinal Acceleration and Corrected Lateral Acceleration.

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Longitudinal Acceleration in g's and Corrected Lateral Acceleration in g's. The top pane has a range of -0.8 to 0.1 g in 0.2-g increments and the bottom pane has a range of -1 to 0.1 g in 0.2-g increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 4 seconds in 0.5-second increments.

The upper pane has two traces that represent the measured Longitudinal Acceleration for Test 289 conducted by Driver A and Test 336 conducted by Driver C. These two traces have a similar shape, but have different "timing" due to the timing of the brake pulse as shown in the lower pane in Figure 7.18. Both traces start near the origin and drop relatively smoothly at first and then sharply. The smooth transition is due to the handwheel input and the sharp negative peak is due the brake pulse application. The timing of the sharp decrease in the longitudinal acceleration for each test is slightly delayed from that for the brake pulse described in Figure 7.18. Test 289 has a negative peak of –0.65 g at 1.7 seconds and Test 336 has a negative peak of –0.75 g at 1.35 seconds. Both traces then return to approximately –0.15 g with some minor oscillations for the remainder of the time history shown.

The lower pane also has two traces that represent the Corrected Lateral Acceleration for Tests 229 and 336 (Drivers A and C respectively). These two traces have a similar shape, but have different "timing" due to the timing of the brake pulse as shown in the lower pane in Figure 7.18. Both traces start near the origin and drop sharply to –0.6 g at 0.5 seconds. Both traces tend to decrease (become more negative) with some oscillation in response until the point of brake application. When the brake application occurs, the magnitude of the Corrected Lateral Acceleration becomes less negative and then decreases very rapidly after the brake application is released. The response is fairly oscillatory after the brake application, but both traces settle out to near -0.6 g by the end of the trace. For Test 289, the trace has a negative peak prior to brake application of –0.7 g at 1.4 seconds, a "dip" in the amplitude due to the braking of –0.25 g at 1.7 seconds, and a decrease back to –0.73 g at 1.85 seconds. This is followed by an oscillatory response that damps out to a level of -0.6 g at 3.1 seconds. The timing for Test 336 is a negative peak of –0.65 g at 1 second, a "dip" of –0.15 g at 1.3 seconds, and a decrease to –0.8 g at 1.5 seconds. Again, this is followed by an oscillatory response that damps out to a level of -0.6 g at 3.1 seconds.

Figure 7.20: J-Turn with Pulse Brake Driver Comparison – Roll Angle and Roll Velocity.

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Roll Angle in degrees and Roll Rate in degrees/second. The top pane has a range of 2 to 11 degrees in 2-degree increments and the bottom pane has a range of -35 to 60 degrees/second in 10-degrees/second increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 4 seconds in 0.5-second increments.

The upper pane has two traces that represent the Roll Angle for Test 289 conducted by Driver A and Test 336 conducted by Driver C. These two traces have a similar shape, but have different "timing" due to the timing of the brake pulse as shown in the lower pane of Figure 7.18. Both traces start near the origin and increase rapidly to approximately 5 degrees near 0.5 seconds. The response tends to increase with some oscillation until the point of brake application at which point the roll angle decreases sharply and then rises rapidly after the brake application is released. The timing of the sharp decrease in the roll angle for each test is slightly delayed from that for the brake pulses described in Figure 7.18. Test 289 has a positive peak of 5.8 degrees at 1.5 seconds. This trace then decreases to 1 degree at 1.75 seconds and rises to 9 degrees at 2.2 seconds. This is followed by an oscillatory response that is centered around 5 degrees for the remainder of the test. Test 336 has a positive peak of 5.8 degrees at 1.1 seconds. This trace then decreases to –0.5 degrees at 1.35 seconds and rises to 10 degrees at 1.75 seconds. This is followed by an oscillatory response that is centered around 5 degrees for the remainder of the test.

The lower pane also has two traces that represent the Roll Velocity for Tests 229 and 336 (Drivers A and C respectively). These two traces have a similar shape, but have different "timing" due to the timing of the brake pulse as shown in the lower pane in Figure 7.18. Both traces start near the origin and have several positive oscillations in response until the onset of brake application. The responses then have a negative peak followed by large positive peak. The large positive peak is then followed by an oscillatory response. Test 289 has three positive peaks prior to the onset of braking. The peaks are approximately 18 degrees/second at 0.4 seconds, 10 degrees/second at 0.8 seconds and 6 degree/second at 1.8 seconds. The troughs in between these peaks are near 0 degrees/second. These positive peaks are followed by a large negative trough value of –20 degrees/second at 1.65 seconds and a positive peak value of 40 degrees/second at 1.9 seconds. The trace then has decreasing amplitude oscillations that start near +/- 10 degrees/second. Test 336 has two positive peaks prior to the onset of braking. The peaks are approximately 15 degrees/second at 0.4 seconds and 9 degrees/second at 0.8 seconds. The trough in between these peaks is near 0 degrees/second. These positive peaks are followed by a large negative trough value of –25 degrees/second at 1.2 seconds and a positive peak value of 51 degrees/second at 1.5 seconds. The trace then has decreasing amplitude oscillations that start near +/- 10 degrees/second. The oscillations for Test 336 do not damp out as quickly as those for Test 289.

Figure 7.21: Vehicle Speed and Handwheel Angle for 4Runner Matched Tests 41-A, 78-B, and 111-C.

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Speed in mph and Handwheel Angle in degrees. The top pane has a range of 10 to 45 mph in 5-mph increments and the bottom pane has a range of -400 to +800 degrees in 200-degree increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 6 seconds in 1-second increments.

The upper pane has three traces that represent the measured Vehicle Speed for Test 41 Driver A, Test 78 Driver B, and Test 111 Driver C. The solid line, indicating Test 41 Driver A, begins at 35 mph and falls very gradually down to 32.5 mph at 2 seconds, 18 mph at 4 seconds, and 15 mph by 6 seconds. The dashed line, indicating Test 78 Driver B, also begins at 35 mph point, but falls even less rapidly than the solid line. It is down to 34 mph at 2 seconds, 22 mph at 4 seconds, and 17 mph at 6 seconds. The dotted line, indicating Test 111 Driver C, also begins at 35 mph. It is down to 34 mph at 2 seconds, 22 mph at

4 seconds and 15 mph at 6 seconds. There is an unusual hump in this trace due to the fifth wheel losing contact with the ground. The hump occurs between 2.5 and 3 seconds.

The lower pane has three traces that represent the measured Handwheel Angle for Test 41 Driver A, Test 78 Driver B, and Test 111 Driver C. The three traces are very similar to each other for the first second. All three traces start near the origin and curve down (gradually at first and then more sharply) to -270 degrees at 0.7 second. All three traces remain at this level until 1 second. At 1 second, Test 41 reverses direction and rises to 700 degrees at 2.5 seconds. It stays at this level until 4 seconds and then reverses and heads back towards the x-axis. At 1 second, Test 78 also reverses direction and rises to 450 degrees at 2 seconds. It gradually descends from this level to 270 degrees at 6 seconds. From 1 second to 1.3 seconds, Test 111 continues to remain flat at -270 degrees and then reverses direction and rise to 750 degrees at 2.9 seconds. It stays at this level until 5 seconds and then reverses and heads back towards the x-axis.

Figure 7.22: Lateral Acceleration and Roll Angle for 4Runner Matched Tests 41-A, 79-B, and 111-C

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Corrected Lateral Acceleration in g's and Roll Angle in degrees. The top pane has a range of –0.8 to 0.8 g in 0.2-g increments and the bottom pane has a range of -10 to 10 degrees in 5-degree increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 6 seconds in 1-second increments.

The upper pane has three traces that represent the Corrected Lateral Acceleration for Test 41 Driver A, Test 78 Driver B, and Test 111 Driver C. The three traces are very similar to each other for the first one second. All three traces start near the origin and curve down (gradually at first and then more sharply) to –0.65 g at 1 second. At this point, the solid line, representing Test 41, rises to 0.65 g at 2 seconds where a series of 4 peaks follow this one. These apexes are at: 2.5 seconds, 0.78 g; 3.2 seconds, 0.75 g; 3.6 seconds, 0.6 g; and 4 seconds, 0.65 g. The line remains flat at this level for about 0.5 second before returning toward the x-axis. At 1 second, the dashed line, representing Test 78, also rises to 0.65 g at but reaches this height slightly ahead of the solid line for Test 41 (1.9 seconds). It also has four peaks that follow this initial one and they are located at: 2.3 seconds, 0.7 g; 2.9 seconds, 0.77 g; 3.6 seconds, 0.77 g; and 4 seconds, 0.6 g's. The line then remains fairly flat out to 5 seconds and then decreases to 0.4 g at 6 seconds. The dotted line, representing Test 111, stays near –0.65 g for a longer period than the other tests and start to reverse direction at 1.5 seconds. It reaches a peak of 0.6 g at 2 seconds. This is followed by three peaks located at: 2.6 seconds, 0.7 g; 3.1 seconds, 0.65 g; and 3.5 seconds, 0.65 g. The trace than has slight undulations centered at 0.6 g until 5.5 seconds. The trace then decreases to 0.3 g at 6 seconds.

The lower pane has three traces that represent the Roll Angle for Test 41 Driver A, Test 78 Driver B, and Test 111 Driver C. The three traces are very similar to each other for the first one second. All three traces start near the origin and curve up (gradually at first and then more sharply) to 7 degrees at 1 second. At this point, the solid line, representing Test 41, lowers to –8.5 degrees at 2 seconds where a series of 4 negative peaks follow this one. These apexes are at: 2.7 seconds, -8.5 degrees; 2.9 seconds, -9 degrees; 3.4 seconds, -7.5 degrees; and 3.9 seconds, -7 degrees. The line remains flat at this level for about 0.5 second before returning towards the x-axis. At 1 second, the dashed line, representing Test 78, lowers to –8 degrees but reaches this height slightly ahead of the solid line for Test 41 (1.9 seconds). It also has four negative peaks that follow this initial one and they are located at: 2.3 seconds, -8 degrees; 3.2 seconds, -9 degrees; 3.8 seconds, - 8 degrees; and 4.2 seconds, -7 degrees. The line then remains fairly flat out to 5 seconds and then increases to -4 g at 6 seconds. The dotted line, representing Test 111, stays near 7 degrees for a longer period than the other tests and start to reverse direction at 1.5 seconds. It reaches a negative peak of –8 degrees at 2.2 seconds. This is followed by three peaks located at: 2.8 seconds, -7.5 degrees; 3.2 seconds, -8 degrees; and 3.8 seconds, -7.5 degrees. The trace then has slight undulations near -7 degrees until 5.5 seconds. The trace then increases to 5 degrees at 6 seconds.

Figure 7.23: Vehicle Speed and Handwheel Angle for 4Runner Matched Tests 32-A, 38-A, 58-A, 68-B, 99-C, and 106-C

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Speed in mph and Handwheel Angle in degrees. The top pane has a range of 10 to 45 mph in 5-mph increments and the bottom pane has a range of -800 to +400 degrees in 200-degree increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 6 seconds in 1-second increments.

The upper pane has six traces that represent the measured Vehicle Speed for Tests 32, 38, and 58 Driver A, Test 68 Driver B, and Tests 99 and 106 Driver C. All 6 traces start at 35 mph and remain relatively flat until 0.8 seconds. The traces then start to slope downward, more slowly at first. The solid lines, indicating Driver A, fall very gradually down to 30 mph at 2.5 seconds, 20 mph at 4 seconds, and 15 mph by 6 seconds. The dashed line, indicating Driver B, also begins at 35 mph point, but falls less rapidly than the solid lines. It is down to 32 mph at 2.5 seconds, 25 mph at 4 seconds, and by 19 mph at 6 seconds. The dotted lines, indicating Driver C, fall between those for Driver A and Driver B.

The lower pane has six traces that represent the measured Handwheel Angle for Tests 32, 38, and 58 Driver A, Test 68 Driver B, and Tests 99 and 106 Driver C. The six traces are very similar to each other for the first one second. All three traces start near the origin and curve up (gradually at first and then more sharply) to 270 degrees at 0.7 second. All six traces remain at this level until 1 second. At 1 second the traces start to diverge, but all have the same basic shape of reversing direction and going to –800 degrees where they remain flat until they reverse direction again. The one exception to this is Test 68, which only gets to –500 degrees where it stays relatively flat before reversing direction. The tests for Driver C start the first reversal near 1 second and reach –800 degrees near 2.5 seconds. The traces for these tests remain relatively flat until 5.6 seconds and then start to slowly reverse and reach -600 degrees at 6 seconds. Driver B reverses direction near 1.3 seconds and reaches -500 degrees near 2.5 seconds. This trace remains relatively flat until 5 seconds and then slowly reverses reaching –200 degrees at 6 seconds. The traces for Driver A start the first reversal over a range from 1.3 to 1.5 seconds and reach –800 degrees between 3 and 3.5 seconds. These traces then reverse direction again near 4.2 seconds reaching approximately –100 degrees at 6 seconds.

Figure 7.24: Lateral Acceleration and Roll Angle for 4Runner Matched Tests 32-A, 38-A, 58-A, 68-B, 99-C, and 106-C

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Corrected Lateral Acceleration in g's and Roll Angle in degrees. The top pane has a range of –0.8 to 0.8 g in 0.2-g increments and the bottom pane has a range of –7.5 to 12.5 degrees in 5-degree increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 6 seconds in 1-second increments.

The upper pane has six traces that represent the corrected lateral acceleration for Tests 32, 38, and 58 Driver A, Test 68 Driver B, and Tests 99 and 106 Driver C. All of the traces have the same basic shape of starting near the origin, increasing to approximately 0.7 g and then reversing direction and reaching negative peaks of -0.65 to -0.8 g. This is followed by several oscillations before starting to return to zero g. Corresponding to the handwheel angles presented in Figure 7.23, the corrected lateral acceleration traces for Driver C reverse direction more quickly than Driver B and Driver B's trace reverses direction more quickly than those for Driver A.

The lower pane has six traces that represent the roll angle for Tests 32, 38, and 58 Driver A, Test 68 Driver B, and Tests 99 and 106 Driver C. All of the traces have the same basic shape of starting near the origin, decreasing to approximately –6.5 degrees and then reversing direction and reaching peaks of 8 to 10 degrees. This is followed by several oscillations before starting to return to zero degrees. Corresponding to the handwheel angles presented in Figure 7.23, the roll angle traces for Driver C reverse direction more quickly than Driver B and Driver B's trace reverses direction more quickly than those for Driver A.

Figure 7.25: Vehicle Speed and Handwheel Angle for Bronco II Matched Tests 33-A, 180-B, and 357-C.

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Speed in mph and Handwheel Angle in degrees. The top pane has a range of 10 to 45 mph in 5-mph increments and the bottom pane has a range of -800 to +400 degrees in 200-degree increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 6 seconds in 1-second increments.

The upper pane has three traces that represent the measured Vehicle Speed for Test 33 Driver A, Test 180 Driver B, and Test 357 Driver C. The solid line, indicating Test 33-A begins at 43 mph and falls very gradually down to 35 mph at 2 seconds, 20 mph at 4 seconds, and 12 mph by 5 seconds where it remains to end of timeline. The dashed line, indicating Test 180-B begins at the same point, but falls even less quickly than the solid line. By 2 seconds about 40 mph, by four seconds 22 mph, and by 6 seconds it falls down to 17 mph. The dotted line for test 357-C, begins as the previous two, but falls even less quickly than the dashed line to about 41 mph by 2 seconds, 31 mph at 4 seconds, and 18 mph at 6 seconds.

The lower pane has three traces that represent the measured Handwheel Angle for Test 33 Driver A, Test 180 Driver B, and Test 357 Driver C. The solid line, for Test 33-A, begins at the origin and begins a gradual ascent up to 270 degrees at 0.5 second, where it remains flat for about a half second before falling gradually to a low of approximately -500 degrees at 3.0 seconds. The trace remains at this level for about 2 seconds before it begins to rise at 5 seconds. It reaches –200 degrees at 6 seconds. The dashed line, for Test 180-B, begins near the origin. It rises to about 270 degrees at 1 second then falls more rapidly and sooner than the solid line to –400 degrees at 2 seconds where it remains flat until 5.3 seconds where it ascends to –200 degrees at 6 seconds. The dotted line, for Test 357-C, also begins near the origin rises to 270 degrees at 0.75 seconds, then falls to a low at –750 degrees at 2.5 seconds, where it remains flat out to 6 seconds.

Figure 7.26: Lateral Acceleration and Roll Angle for Bronco II Matched Tests 33-A, 180-B, and 357-C.

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Corrected Lateral Acceleration in g's and Roll Angle in degrees. The top pane has a range of –0.8 to 0.8 g in 0.2-g increments and the bottom pane has a range of -10 to 10 degrees in 5-degree increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 6 seconds in 1-second increments.

The upper pane has three traces that represent the Corrected Lateral Acceleration for Test 33 Driver A, Test 180 Driver B, and Test 357 Driver C. The solid line, for test 33-A begins at the origin and remains flat for about 0.2 seconds before climbing to 0.7 g at 1 second. The trace rises slightly again to 0.75 g at 1.5 seconds before falling to 0.3 g at 2 seconds, then down to -0.7 g at 2.3 seconds. This is followed by a series of negative peak values at 3.1 seconds, -0.8 g; 3.6 seconds, -0.7 g; 4 seconds, -0.65 g; 4.6 seconds, -0.65 g. The trace then reduces to –0.15 g at 6 seconds. The dashed line, for Test 180-B, begins at 0.1 g and 0 seconds and rises to 0.65 g at 1 second. It then drops to –0.65 g at 1.8 seconds. This is followed by several oscillations with negative peaks of –0.7 g at 2.6 seconds, -0.65 g at 3.1 seconds, and –0.65 g at 3.6 seconds. The trace then rises to –0.35 g at 4.2 seconds, drops to –0.55 g at 5 seconds and ends at –0.35 g at 6 seconds. The Dotted Line, for test 357-C follows the solid line very closely until 1.3 seconds. A peak is reached at 1 second and 0.7 g and then the trace drops to -0.7 g at 1.8 seconds. This is followed by negative peak values of –0.65 g at 2.6 seconds and –0.6 g at 3.1 seconds. The trace then rises to –0.15 g at 3.6 seconds and then falls to –0.5 g at 4.1 seconds. The trace then has slight undulations near –0.5 g for the remainder of the trace.

The lower pane has three traces that represent the Roll Angle for Test 33 Driver A, Test 180 Driver B, and Test 357 Driver C. The solid line, Test 33-A, begins at the origin and remains flat for about 0.5 second before falling to –5 degrees at 0.6 seconds where it remains relatively flat (small undulations) for about 1 second before rising steeply to 7.5 degrees at 2.6 seconds. This is followed by a series of 5 peaks at the following locations: 3.2 seconds, 6 degrees; 3.8 seconds, 7 degrees; 4.2 seconds, 6 degrees; 4.6 seconds, 6 degrees; 5.1 seconds, 4 degrees. At this point the trace remains relatively flat at 2 degrees for the remainder of the timeline. The dashed line, Test 180-B also starts near the origin. The initial descent is slower than that for Test 33 and reaches a negative peak of –5.5 degrees at 1.1 seconds before it ascends to a peak of 9 degrees at 2 seconds. This is followed by 3 small undulations with peaks located at 2.5 seconds and 8.5 degrees, 3.2 seconds and 8 degrees, 3.9 seconds and 7 degrees, before the line dips down to a low spot at 4.3 seconds and 5 degrees. The trace then slowly rises 6 degrees at 5 seconds and then drops and then slowly decreases to 4 degrees at 6 seconds. The dotted line, Test 357-B, begins at the origin. The initial negative peak is –5 degrees at 0.8 seconds followed by a small positive peak at 0.9 seconds and -4 degrees, followed by a second negative peak of –5.5 degrees at 1.2 seconds. The line then ascends to a peak at 2 seconds and 8 degrees followed by a series of undulations around 5 degrees that taper off to 4 degrees at the end of the timeline.

Figure 8.1: LAR as a Function of Vehicle Roll Inertia for the Ford Bronco II – Linear Interpolation

The y-axis is labeled LAR in g and has a range of 0 to 0.8 g in 0.1-g increments. The x-axis is labeled Roll Inertia in ft-lb-sec^2 and has a range of 400 to 750 ft-lb-sec^2 in 50-ft-lb-sec^2 increments. The data for the Left-Right steer data points are labeled with diamonds while the Right-Left steer data points are labeled with squares. Both traces have a decreasing trend. The Left-Right trace starts near 0.78 g at 460 ft-lb-sec^2 and decreases linearly to 0.77 g at 540 ft-lb-sec^2 and 0.74 g at 670 ft-lb-sec^2. The Right-Left trace starts near 0.72 g at 460 ft-lb-sec^2 and decreases linearly to 0.71 g at 540 ft-lb-sec^2 and 0.70 g at 670 ft-lb-sec^2.

Figure 8.2: Minimum Speed Required to Produce Two-Wheel Lift as a Function of Vehicle Roll Inertia for the Ford Bronco II- Linear Interpolation.

The y-axis is labeled Speed in mph and has a range of 0 to 50 mph in 10-mph increments. The x-axis is labeled Roll Inertia in ft-lb-sec^2 and has a range of 400 to 700 ft-lb-sec^2 in 50-ft-lb-sec^2 increments. The data for the Left-Right steer data points are labeled with diamonds while the Right-Left steer data points are labeled with squares. Both traces have an increasing trend. The Left-Right trace starts near 40 mph at 460 ft-lb-sec^2 and increases linearly to 45 mph at 670 ft-lb-sec^2. The Right-Left trace starts near 39 mph at 460 ft-lb-sec^2 and increases linearly to 44 mph at 670 ft-lb-sec^2.

Figure 8.3: Vehicle Speed and Handwheel Angle for Bronco II Matched Tests 37.7 mph – Unballasted and Ballasted Outriggers

This figure contains 2 subplots or “panes”. The top and bottom pane y-axis labels are, respectively, Speed in mph and Handwheel Angle in degrees. The top pane has a range of 10 to 40 mph in 5-mph increments and the bottom pane has a range of -300 to +600 degrees in 100-degree increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 6 seconds in 1-second increments.

The upper pane has four traces that represent the measured Vehicle Speed for Tests 009 and 048 – Unballasted Outriggers and Tests 054 and 055 – Ballasted Outriggers. The four traces are indistinguishable from each other from 0 to 2.5 seconds. They start at 37 mph at 0 seconds and fall to 30 mph at 2.5 seconds. The solid line, indicating Test 009 Unballasted, then gradually falls to 15 mph at 4 seconds, and remains flat out to 6 seconds. The dashed line indicating Test 048 Unballasted, gradually falls to 20 mph at 4 seconds, and 18 mph at 5 seconds where it remains flat for the duration of the trace. The dotted line for Test 054 Ballasted falls at an even slower rate than the first two. By 4 seconds it is at 20 mph, and by 5 seconds, 18 mph where it remains flat for the duration of the trace. The dash dot line for Test 055 Ballasted falls even more slowly at first. The speed at 4 seconds is 22 mph, and by 5 seconds 17 mph, where the trace remains flat until the end of the timeline.

The lower pane has four traces that represent the measured Handwheel Angle for Tests 009 and 048 – Unballasted Outriggers and Tests 054 and 055 – Ballasted Outriggers. The four traces are indistinguishable for the first 1.1 seconds with all four starting at the origin and dropping (more gradually at first) to –270 degrees at 0.7 seconds where they all remain flat until at least 1.1 seconds. The solid line, for Test 009 Unballasted, starts to reverse direction at 1.1 seconds and reaches a peak height of about 500 degrees at 2.8 seconds where it remains relatively flat for about 2 seconds before it begins to fall. By 4.5 seconds it is down to 300 degrees and by 5 seconds to 150 degrees where it remains flat for the rest of the timeline. The dashed line, for Test 048 Unballasted, has a very similar shape as that for Test 009, but only reaches a height of 450 degrees. The dotted line, for test 054 Ballasted, is also very similar to the first two, but only reaches a height of approximately 400 degrees. The dash-dot line for Test 055 Ballasted starts its steering reversal at 1.3 seconds climbing to 400 degrees at 2.2 seconds where it remains flat until 5 seconds. It then starts to descend dropping to 100 degrees at 5.5 seconds where it remains flat for the duration of the timeline.

Figure 8.4: Corrected Lateral Acceleration and Roll Angle Traces for Bronco II Matched Tests 37.7 mph – Unballasted and Ballasted Outriggers

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Corrected Lateral Acceleration in g's and Roll Angle in degrees. The top pane has a range of –0.8 to 0.8 g in 0.2-g increments and the bottom pane has a range of -10 to 8 degrees in 2-degree increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 6 seconds in 1-second increments.

The upper pane has four traces that represent Corrected Lateral Acceleration for Tests 009 and 048 – Unballasted Outriggers and Tests 054 and 055 – Ballasted Outriggers. The four traces are very similar for the first 1.5 seconds. They all start near the origin and remain relatively flat for approximately 0.2 seconds before descending to –0.7 g at 1 seconds. They remain fairly flat at this level until approximately 1.5 seconds where they start to reverse direction and rise to approximately 0.7 g. The solid line, for Test 009, rises to 0.7 g at approximately 2.1 seconds. This is followed by several oscillations before the trace starts to descend at 4 seconds. The trace reaches 0.15 g at 5 seconds where it remains relatively flat. The dashed line, Test 048, follows the same path as the solid line, but reaches 0.7 g at 2 seconds. This trace also has several oscillations, before dropping to 0.4 g's at 5 seconds where it remains. The dotted line, Test 054, follows the solid line most closely to the first peak of 0.7 g and through the oscillations. It has a similar, although somewhat later, descent to 0.15 g. The dash-dot trace, Test 055, reaches 0.7 g at 2.2 seconds. This trace also has several oscillations and does not start to descend until somewhat later than the other tests, starting at 5 seconds and reaching 0.1 g at 6 seconds.

The lower pane has four traces that represent the Roll Angle for Tests 009 and 048 – Unballasted Outriggers and Tests 054 and 055 – Ballasted Outriggers. The four traces are very similar for the first 1.5 seconds. They all start near the origin and remain relatively flat for approximately 0.25 seconds before ascending to 5 degrees at 0.8 seconds. They remain fairly flat at this level until approximately 1.5 seconds where they start to reverse direction. The solid line (Test 009) reaches a negative peak of –8.5 degrees at 2.4 seconds. The trace then has a generally increasing trend to 0 degrees at 5 seconds with several small oscillations. The other traces have this same basic shape. The dashed line (Test 048) also reaches –8.5 degrees at 2.4 seconds. The dotted line (Test 054) reaches –7.5 degrees at 2.5 seconds before trending upward and the dash-dot line (Test 055) reaches –7 degrees at 2.4 seconds before trending upward.

Figure 8.5: Roll Rate and Yaw Rate for Bronco II Matched Tests 37.7 mph – Unballasted and Ballasted Outriggers

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Roll Rate and Yaw Rate both in degrees/second. The top pane has a range of –40 to 20 degrees/second in 10-degrees/second increments and the bottom pane has a range of -40 to 60 degrees/second in 20-

degrees/second increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 6 seconds in 1-second increments.

The upper pane has four traces that represent the Roll Rate for Tests 009 and 048 – Unballasted Outriggers and Tests 054 and 055 – Ballasted Outriggers. All four traces have the same basic shape: start at the origin, stay flat for a short period (0.25 seconds), ramp up to a positive peak, reverse direction to a negative peak and then an oscillatory response of $\pm$10 degrees. The solid line (Test 009) reaches an initial peak of 17 degrees/second at 0.5 seconds followed by a negative peak of –36 degrees/second at 2.1 seconds. The dashed line (Test 048) reaches an initial peak of 15 degrees/second at 0.6 seconds followed by a negative peak of –35 degrees/second at 2 seconds. The dotted line (Test 054) reaches an initial peak of 16 degree/second at 0.5 seconds followed by a negative peak of –27 degrees/second at 2.1 seconds. The dashed-dot line (Test 055) reaches an initial peak of 16 degree/second at 0.7 seconds followed by a negative peak of –28 degrees/second at 2.2 seconds.

The lower pane has four traces that represent the Yaw Rate for Tests 009 and 048 – Unballasted Outriggers and Tests 054 and 055 – Ballasted Outriggers. All four traces have the same basic shape: start at the origin, stay flat for a short period (0.3 seconds), ramp down to a negative peak, reverse direction to a positive peak, and then go through a trough to peak to a trough. The solid line (Test 009) has an initial negative peak of -35 degrees/second at 0.8 seconds and stays relatively flat before reversing directions at 1.5 seconds and reaching a positive peak of 50 degrees/second at 2.3 seconds. This is followed by a trough of 18 degrees/second at 4 seconds, peak of 42 degrees/second at 4.5 seconds, and a trough of 15 degrees/second at 5.5 seconds. The dashed line (Test 048) has an initial negative peak of -35 degrees/second at 0.8 seconds and stays relatively flat before reversing directions at 1.5 seconds and reaching a positive peak of 45 degrees/second at 2.2 seconds. This is followed by a trough of 17 degrees/second at 3.8 seconds, peak of 42 degree/second at 4.3 seconds, and a trough of 20 degrees/second at 5.5 seconds. The dotted line (Test 054) has an initial negative peak of -30 degrees/second at 0.8 seconds and stays relatively flat before reversing directions at 1.5 seconds and reaching a positive peak of 45 degrees/second at 2.3 seconds. This is followed by a trough of 18 degrees/second at 4 seconds, peak of 40 degree/second at 4.8 seconds, and a trough of 15 degrees/second at 5.2 seconds. The dashed-dot line (Test 055) has an initial negative peak of 30 degrees/second at 0.8 seconds and stays relatively flat before reversing directions at 1.7 seconds and reaching a positive peak of 42 degrees/second at 2.6 seconds. This is followed by a trough of 20 degrees/second at 4.1 seconds, peak of 42 degree/second at 5 seconds, and a trough of 10 degrees/second at 5.9 seconds.

Figure 8.6: Vehicle Speed and Handwheel Angle for Bronco II Matched Tests 44.4 mph – Unballasted and Ballasted Outriggers

This figure contains 2 subplots or “panes”. The top and bottom pane y-axis labels are, respectively, Speed in mph and Handwheel Angle in degrees. The top pane has a range of 0 to 50 mph in 10-mph increments and the bottom pane has a range of -600 to +300 degrees in 200-degree increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 6 seconds in 1-second increments.

The upper pane has three traces that represent the measured Vehicle Speed for Tests 034 and 035 – Unballasted Outriggers and Tests 070 and 072 – Ballasted Outriggers. The four traces are indistinguishable from each other from 0 to 2.5 seconds. They start at 45 mph at 0 seconds and fall to 35 mph at 2.5 seconds. The solid line, indicating Test 034 Unballasted, then gradually falls to 9 mph at 5 seconds, and remains relatively flat out to 6 seconds. The dashed line indicating Test 035 Unballasted, gradually falls to 10 mph at 4.8 seconds and remains flat for the duration of the trace. The dotted line for Test 070 Ballasted falls at slower rate than the first two dropping to 11 mph at 5 seconds where it remains. The dash dot line for Test 072 Ballasted falls to 8 mph at 5.1 seconds where the trace remains flat until the end of the timeline.

The lower pane has three traces that represent the measured Handwheel Angle for Tests 034 and 035 – Unballasted Outriggers and Tests 070 and 072 – Ballasted Outriggers. The four traces are very similar for the first 1.5 seconds with all four starting at the origin and rising (more gradually at first) to 270 degrees at 0.5 seconds where they all remain flat until approximately1 second where the steering reversal starts. All four traces are at approximately 0 degrees by 1.5 seconds. The solid line, for Test 034 Unballasted, continues downward until it reaches a negative peak of about 500 degrees at 3 seconds where it remains relatively flat for approximately 2 seconds before it begins to rise. At 6 seconds it has reached –200 degrees. The dashed line, for Test 035 Unballasted, has a very similar shape as that for Test 034, but reaches a lower negative peak of -550 degrees. The dotted line, for test 070 Ballasted, is also very similar to the first two, but only reaches a negative peak of approximately -450 degrees. The dash-dot line for Test 072 Ballasted only reaches a negative peak of -400 degrees at 2.5 seconds where it remains flat until 4.2 seconds where it starts to ascend. This trace rises to -200 degrees at 5.2 seconds and remains at this level for the duration of the test.

Figure 8.7: Corrected Lateral Acceleration and Roll Angle Traces for Bronco II Matched Tests – 44.4 mph – Unballasted and Ballasted Outriggers

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Corrected Lateral Acceleration in g's and Roll Angle in degrees. The top pane has a range of –0.8 to 0.8 g in 0.2-g increments and the bottom pane has a range of –7.5 to 10 degrees in 5-degree increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 6 seconds in 1-second increments.

The upper pane has four traces that represent Corrected Lateral Acceleration for Tests 034 and 035 – Unballasted Outriggers and Tests 070 and 072 – Ballasted Outriggers. The four traces are very similar for the first 1.7 seconds. They all start near the origin and remain relatively flat for approximately 0.1 seconds before ascending to 0.7 g at 1 second. They remain at this level until approximately 1.7 seconds where they start to reverse direction and lower to approximately -0.7 g. The solid line, for Test 034, lowers to -0.7 g at approximately 2.3 seconds. This is followed by several oscillations before the trace starts to ascend at 4.8 seconds. The trace reaches -0.1 g at 5.5 seconds where it remains relatively flat. The dashed line, Test 035, follows the same path as the solid line, but reaches -0.7 g at 2.2 seconds. This trace also has several oscillations before ascending to -0.2 g at 5 seconds where it remains. The dotted line, Test 070, reaches -0.7 g and also has several oscillations before starting to ascend at 5 seconds, reaching –0.1 g at 5.3 seconds. The dash-dot trace, Test 072, reaches 0.7 g at 2.4 seconds. This trace also has several oscillations and does not start to ascend until 5 seconds, reaching 0.15 g at 5.7 seconds and then dropping to –0.15 g at 6 seconds.

The lower pane has four traces that represent the Roll Angle for Tests 034 and 035 – Unballasted Outriggers and Tests 070 and 072 – Ballasted Outriggers. The four traces are very similar for the first 1.5 seconds. They all start near the origin and remain relatively flat for approximately 0.25 seconds before descending to -5 degrees at 0.75 seconds. They remain at this level until approximately 1.6 seconds where they start to reverse direction. The solid line (Test 009) reaches a peak of 8.5 degrees at 2.7 seconds. The trace then drops to the 5 degrees and goes through a series of four oscillations before dropping to the 1 degree with two small oscillations. The dashed line (Test 035) has a very similar shape, but has a slightly higher first peak of 9 degrees. The dotted line (Test 070) reaches 9 degrees at 2.8 seconds and stays at a higher level (7 degrees) with smaller oscillations until starting to descend near 5 seconds. The dashed-dot line (Test 072) is very similar to 070, but it reaches 9.5 degrees at 2.8 seconds and does not start to descend until 5.2 seconds.

Figure 8.8: Roll Rate and Yaw Rate for Bronco II Matched Tests 44.4 mph – Unballasted and Ballasted Outriggers

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Roll Rate and Yaw Rate both in degrees/second. The top pane has a range of –40 to 40 degrees/second in 20-degree/second increments and the bottom pane has a range of -60 to 40 degrees/second in 20-degree/second increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 6 seconds in 1-second increments.

The upper pane has four traces that represent the Roll Rate for Tests 034 and 035 – Unballasted Outriggers and Tests 070 and 072 – Ballasted Outriggers. All four traces have the same basic shape: start at the origin, stay flat for a short period (0.25 seconds), ramp down to a negative peak, reverse direction with an oscillatory response to a positive peak and then an oscillatory response of $\pm$10 degrees. The solid line (Test 034) reaches an initial negative peak of -20 degrees/second at 0.5 seconds followed by a positive peak of 35 degrees/second at 2.4 seconds. The dashed line (Test 035) reaches an initial negative peak of -18 degrees/second at 0.4 seconds followed by a positive peak of 37 degrees/second at 2.3 seconds. The dotted line (Test 070) reaches an initial negative peak of -18 degrees/second at 0.5 seconds followed by a positive peak of 30 degrees/second at 2.5 seconds. The dashed-dot line (Test 055) reaches an initial negative peak of -18 degrees/second at 0.5 seconds followed by a positive peak of 30 degrees/second at 2.5 seconds.

The lower pane has four traces that represent the Yaw Rate for Tests 034 and 035 – Unballasted Outriggers and Tests 070 and 072 – Ballasted Outriggers. All four traces have the same basic shape: start at the origin, stay flat for a short period (0.3 seconds), ramp up to a peak, reverse direction to a negative peak, and then go through a trough to a negative peak to a trough. The solid line (Test 034) has an initial peak of 30 degrees/second at 0.8 seconds and stays relatively flat before reversing directions at 1.8 seconds and reaching a negative peak of -50 degrees/second at 2.2 seconds. This is followed by a trough of -10 degrees/second at 4.8 seconds, negative peak of -35 degrees/second at 5.2 seconds, and a trough of 18 degrees/second at 6 seconds. The dashed line (Test 035) has an initial peak of 30 degrees/second at 0.8 seconds and stays relatively flat before reversing directions at 1.7 seconds and reaching a negative peak of -50 degrees/second at 2.1 seconds. This is followed by a trough of 0 degrees/second at 4.7 seconds, negative peak of -36 degrees/second at 5 seconds, and a trough of 18 degrees/second at 5.8 seconds. The dotted line (Test 070) has an initial peak of 30 degrees/second at 0.8 seconds and stays relatively flat before reversing directions at 1.8 seconds and reaching a negative peak of -50 degrees/second at 2.5 seconds. This is followed by a trough of -15 degrees/second at 5 seconds, negative peak of -30 degrees/second at 5.4 seconds, and a trough of 18 degrees/second at 5.8 seconds. The dashed-dot line (Test 072) has an initial peak of 30 degrees/second at 0.8 seconds and stays relatively flat before reversing directions at 1.8 seconds and reaching a negative peak of -50 degrees/second at 2.4 seconds. This is followed by a trough of -10 degrees/second at 5.2 seconds, negative peak of -12 degrees/second at 5.6 seconds, and a trough of 10 degrees/second at 6 seconds.

Figure 8.9: Corrected Lateral Acceleration Frequency Response – Normal Outriggers

This figure has three sub-plots or “panes”. The x-axis is “Frequency in Hertz” from 0.01 Hz to 10 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axes are labeled Magnitude, Phase, and Coherence from top to bottom. The Magnitude scale has units of g/degree and ranges from 0 to $6x10^{-3}$. The Phase scale has units of degrees and ranges from –400 to 200 degrees. The Coherence scale has a range of 0.4 to 1.0.

The Coherence pane has a single trace that starts at 0.05 Hz and a value of approximately 0.8. The coherence trace then steadily increases to 0.95 at 0.2 Hz, decreases to 0.9 at 0.25 Hz and then increases to nearly 1 at 0.5 Hz and stays near this level until 1.2 Hz. The coherence trace then drops off fairly rapidly which means there is no longer good coherence. This being the case, the phase and magnitude traces will not be discussed above 1.5 Hz.

The Phase pane has three traces: one solid line that represents the calculated mean value and two dashed lines that represent the 95^{th} percentile confidence interval for the mean value. The 95^{th} percentile confidence interval traces are barely discernable from the mean value. The mean value trace also starts at 0.05 Hz and has a value of 0 degrees. The trace slowly ramps down to –50 degrees at 0.7 Hz and then more rapidly to –100 degrees at 1.1 Hz.

The Magnitude pane also has three traces: one solid line that represents the calculated mean value and two dashed lines that represent the 95^{th} percentile confidence interval for the mean value. The 95^{th} percentile confidence interval traces are more discernable for the magnitude than they are for the phase angle. The mean value trace starts at 0.05 Hz and has a value of $4.3x10^{-3}$ g/degree. The trace then rises to $5x10^{-3}$ g/degree at 0.2 Hz and stays at this level until 0.3 Hz. The trace then decreases to $4.1x10^{-3}$ g/degree at 0.7 Hz and $1x10^{-3}$ at 1.5 Hz. The confidence intervals have the same basic shape and are approximately $0.5x10^{-3}$ g/degree above and below the mean value trace at 0.05 Hz and are barely discernable from the mean value by 0.7 Hz.

Figure 8.10: Roll Angle Frequency Response – Normal Outriggers

This figure has three sub-plots or “panes”. The x-axis is “Frequency in Hertz” from 0.01 Hz to 10 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axes are labeled Magnitude, Phase, and Coherence from top to bottom. The Magnitude scale has units of degree/degree and ranges from 0 to 0.1. The Phase scale has units of degrees and ranges from –200 to 200 degrees. The Coherence scale has a range of 0.4 to 1.0.

The Coherence pane has a single trace that starts at 0.05 Hz and a value of approximately 0.9. The coherence trace then remains flat then slowly increases to 0.95 at 0.15 Hz, decreases to 0.85 at 0.20 Hz and then increases to nearly 1 at 0.4 Hz and stays near this level until 1.0 Hz. The coherence trace then drops off fairly rapidly which means there is no longer good coherence. This being the case, the phase and magnitude traces will not be discussed above 1.0 Hz.

The Phase pane has three traces: one solid line that represents the calculated mean value and two dashed lines that represent the 95^{th} percentile confidence interval for the mean value. The 95^{th} percentile confidence interval traces are barely discernable from the mean value. The mean value trace also starts at 0.05 Hz and has a value of -190 degrees. The trace quickly ramps up to 190 degrees at 0.1 Hz and then remains here until 0.2 Hz where the trace falls gradually to 150 degrees at 0.5 Hz then down to 100 degrees at 1 Hz.

The Magnitude pane also has three traces: one solid line that represents the calculated mean value and two dashed lines that represent the 95th percentile confidence interval for the mean value. The 95th percentile confidence interval traces are more discernable for the magnitude than they are for the phase angle. The mean value trace starts at 0.05 Hz and has a value of 0.025 deg/degree. The trace then rises to 0.055 deg/degree at 0.18 Hz and then falls to 0.04 degree/degree at 0.2 Hz. The trace then increases to 0.05 deg/degree at 0.25 Hz and remains at this level out to 0.7 Hz where it falls to 0.3 at 1 Hz. The confidence intervals have the same basic shape and are approximately 0.01 deg/degree above and below the mean value trace at the beginning of the trace and are barely discernable from the mean value by 0.7 Hz.

Figure 8.11: Roll Rate Frequency Response – Normal Outriggers

This figure has three sub-plots or "panes". The x-axis is "Frequency in Hertz" from 0.01 Hz to 10 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axes are labeled Magnitude, Phase, and Coherence from top to bottom. The Magnitude scale has units of degree/second/degree and ranges from 0 to 1. The Phase scale has units of degrees and ranges from –300 to 0 degrees. The Coherence scale has a range of 0 to 1.0.

The Coherence pane has a single trace that starts at 0.05 Hz and a value of approximately 1.0. The coherence trace then remains flat then steadily decreases to 0.80 at 0.15 Hz and stays in this range until 0.25 Hz. It then increases to nearly 1.0 at 0.4 Hz and stays near this level until 1.25 Hz. The coherence trace then drops off fairly rapidly to .37 at 1.8 Hz, which means there is no longer good coherence. This being the case, the phase and magnitude traces will not be discussed above 1.25 Hz.

The Phase pane has three traces: one solid line that represents the calculated mean value and two dashed lines that represent the 95th percentile confidence interval for the mean value. The 95th percentile confidence interval traces are barely discernable from the mean value. The mean value trace also starts at 0.05 Hz and has a value of -180 degrees. The trace quickly ramps up to -100 degrees at 0.15 Hz and remains fairly flat to 0.4 Hz where it then starts to fall (more gradually at first) to –200 degrees at 1 Hz.

The Magnitude pane also has three traces: one solid line that represents the calculated mean value and two dashed lines that represent the 95th percentile confidence interval for the mean value. The 95th percentile confidence interval traces are more discernable for the magnitude than they are for the phase angle. The mean value trace starts at 0.05 Hz and has a value of .10 degree/second/degree. The trace remains flat to 0.20 Hz where it then increases to .2 degree/second/degree at 0.7 Hz then remains here until 1.0 Hz where it falls slowly to 0.15 degree/second/degree by 1.5 Hz. The confidence intervals have the same basic shape and are barely discernable from the mean value.

Figure 8.12: Yaw Rate Frequency Response – Normal Outriggers

This figure has three sub-plots or "panes". The x-axis is "Frequency in Hertz" from 0.01 Hz to 10 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axes are labeled Magnitude, Phase, and Coherence from top to bottom. The Magnitude scale has units of degree/second/degree and ranges from 0 to 0.4. The Phase scale has units of degrees and ranges from –400 to 200 degrees. The Coherence scale has a range of 0.7 to 1.0.

The Coherence pane has a single trace that starts at 0.05 Hz and a value of approximately .85. The coherence trace then steadily increases to 0.97 at 0.2 Hz, decreases to 0.9 at 0.25 Hz and then increases to nearly 1.0 at 0.5 Hz and stays near this level until 1.4 Hz. The coherence trace then drops off which means there is no longer good coherence. This being the case, the phase and magnitude traces will not be discussed above 1.4 Hz.

The Phase pane has three traces: one solid line that represents the calculated mean value and two dashed lines that represent the 95th percentile confidence interval for the mean value. The 95th percentile confidence interval traces are barely discernable from the mean value. The mean value trace also starts at 0.05 Hz and has a value of 0 degrees. The trace ramps down to -50 degrees at 1 Hz and –90 degrees at 1.5 Hz.

The Magnitude pane also has three traces: one solid line that represents the calculated mean value and two dashed lines that represent the 95th percentile confidence interval for the mean value. The 95th percentile confidence interval traces are more discernable for the magnitude than they are for the phase angle. The mean value trace starts at 0.05 Hz and has a value of 0.10 degree/second/degree. The trace rises to 0.2 at 0.3 Hz and then drops slightly to 0.18 and stays at this level until 1.5 Hz. The confidence intervals have the same basic shape and are approximately 0.01 degree/second/degree above and below the mean value near the beginning of the trace and are bare discernable from the mean value at high frequencies.

Figure 8.13: Corrected Lateral Acceleration Magnitude Portion of Frequency Response – Normal Outriggers

In this figure, the x-axis is labeled "Frequency in Hertz" from 0.1 Hz to 2.0 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axis is labeled Magnitude and has units of g/degree and ranges from 0 to 7 x 10^{-3}.

The figure has three traces: one solid line that represents the calculated mean value and two dashed lines that represent the 95th percentile confidence interval for the mean value. The mean value trace starts at 0.1 Hz and has a value of 4.4 x 10^{-3} g/degree. The trace rises to 4.9 x 10^{-3} at 0.2 Hz and stays at this level until 0.3 Hz. The trace then decreases to 4.7 x 10^{-3} g/degree at 0.4 Hz, falls to 4.5 x 10^{-3} g/degree at 0.5 Hz, and then falls more rapidly to 2.5 x 10^{-3} g/degree at 1.0 Hz. The confidence intervals have the same basic shape and are approximately 0.5 x 10^{-3} g/deg above and below the mean value trace at the beginning of the trace and are barely discernable from the mean value by 0.7 Hz.

Figure 8.14: Roll Angle Magnitude Portion of Frequency Response – Normal Outriggers

In this figure, the x-axis is labeled "Frequency in Hertz" from 0.1 Hz to 2.0 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axis is labeled Magnitude and has units of degree/degree and ranges from 0 to 0.07.

There are three traces: one solid line that represents the calculated mean value and two dashed lines that represent the 95th percentile confidence interval for the mean value. The mean value trace starts at 0.10 Hz and has a value of 0.05 degree/degree. The trace rises to 0.056 at 0.16 Hz before falling to 0.044 degree/degree at 0.2 Hz. The trace rises to one more peak at 0.05 degree/degree at 0.25 Hz then falls to a level of 0.048 at 0.35 Hz. The trace stays at this level until 0.45 Hz where it then starts to decrease reaching 0.03 degree/degree at 1.0 Hz and 0.015 at 2 Hz. The confidence intervals have the same basic shape and are approximately 0.5 x 10^{-3} g/deg above and below the mean value trace at the beginning of the trace and are barely discernable from the mean value by 0.7 Hz.

Figure 8.15: Roll Rate Magnitude Portion of Frequency Response – Normal Outriggers

In this figure, the x-axis is labeled "Frequency in Hertz" from 0.10 Hz to 2.0 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axis is labeled Magnitude and has units of degree/second/degree and ranges from 0 to 0.25.

There are three traces: one solid line that represents the calculated mean value and two dashed lines that represent the 95th percentile confidence interval for the mean value. The mean value trace starts at 0.10 Hz and has a value of 0.04 degree/second/degree. The trace then rises slowly to 0.065 at 0.25 Hz. The trace then increases more rapidly to 0.09 at 0.30 Hz and continues to rise to 0.18 at 0.75 Hz. It remains at this level until it starts to fall at 1.0 Hz. The confidence intervals have the same basic shape and are approximately 7.5 x 10^{-3} degree/second/degree above and below the mean value trace at the beginning of the trace and are barely discernable from the mean value by 0.5 Hz.

Figure 8.16: Yaw Rate Magnitude Portion of Frequency Response – Normal Outriggers

In this figure, the x-axis is labeled "Frequency in Hertz" from 0.10 Hz to 2.0 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axis is labeled Magnitude and has units of degree/second/degree and ranges from 0 to 0.25.

There are three traces: one solid line that represents the calculated mean value and two dashed lines that represent the 95th percentile confidence interval for the mean value. The mean value trace starts at 0.10 Hz and has a value of 0.155 degree/second/degree. The trace then rises to 0.18 at 0.3 Hz and then lowers to 0.165 at 0.6 Hz. It then rises again to 0.17 at 0.75 Hz and then lowers gradually to 0.17 at 1 Hz. The confidence intervals have the same basic shape and are approximately 0.015 degree/second/degree above and below the mean value trace at the beginning of the trace and are barely discernable from the mean value by 0.5 Hz.

Figure 8.17: Corrected Lateral Acceleration Frequency Response – Outrigger Comparison

In this figure, the x-axis is labeled "Frequency in Hertz" from 0.10 Hz to 2.0 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axis is labeled Magnitude and has units of g/degree and ranges from 0 to 7.0×10^{-3}.

There are three traces: one solid line that represents the Ballasted Outriggers, one dashed line that represents No Outriggers, and one dotted line that represents the Normal Outriggers. The Ballasted Outrigger trace starts at 0.10 Hz and has a value of 4.8×10^{-3} g/degree. The trace then rises to 5.1×10^{-3} g/degree at 0.25 Hz. The trace then increases sharply to 5.5×10^{-3} g/degree at .30 Hz at which point the trace falls gradually down to 2.5 g/degree at 1.0 Hz. The other two traces have the same basic shape. Both begin slightly below the Ballasted Outrigger line. All three lines cross at approximately 4.4 Hz at a value of 4.5×10^{-3} g/degree. The two Normal Outrigger and No Outrigger traces are then slightly higher than the Ballasted outrigger trace above 4.4 Hz.

Figure 8.18: Roll Angle Frequency Response – Outrigger Comparison

In this figure, the x-axis is labeled "Frequency in Hertz" from 0.10 Hz to 2.0 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axis is labeled Magnitude and has units of degree/degree and ranges from 0 to 0.07.

There are three traces: one solid line that represents the Ballasted Outriggers, one dashed line that represents No Outriggers, and one dotted line that represents the Normal Outriggers. The Ballasted Outrigger trace starts at 0.13 Hz and has a value of 0.07 degree/degree. The trace then falls to 0.055 degree/degree at 0.20 Hz and then rises to a small peak of 0.058 at 0.3 Hz. The trace then decreases sharply to 0.043 at 0.40 Hz and then rises to 0.49 at 0.5 Hz. The trace then falls off to 0.033 at 1.0 Hz. The No Outrigger and Normal Outrigger traces have the same basic shape, but start out approximately 0.02 deg/deg below the Ballasted Outrigger trace at the beginning. By 0.5 Hz the traces are very close to the Ballasted Outrigger trace (solid line).

Figure 8.19: Roll Rate Frequency Response – Outrigger Comparison

In this figure, the x-axis is labeled "Frequency in Hertz" from 0.10 Hz to 2.0 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axis is labeled Magnitude and has units of degree/second/degree and ranges from 0 to 0.25.

There are 3 traces: one solid line that represents the Ballasted Outriggers, one dashed line that represents No Outriggers, and one dotted line that represents the Normal Outriggers. The Ballasted Outrigger trace starts at 0.1 Hz and has a value of 0.035 degree/second/degree. The trace then rises to 0.1 degree/second/degree at .3 Hz and continues upwards until reaching 0.190 at 1 Hz. The Normal Outrigger and No Outrigger traces have the same basic shape. They dip slightly below the Ballasted Outrigger traces in the range of 0.3 to 0.55 Hz.

Figure 8.20: Yaw Rate Frequency Response – Outrigger Comparison

In this figure, the x-axis is labeled "Frequency in Hertz" from 0.10 Hz to 2.0 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axis is labeled Magnitude and has units of degree/second/degree and ranges from 0 to 0.25.

There are 3 traces: one solid line that represents the Ballasted Outriggers, one dashed line that represents No Outriggers, and one dotted line that represents the Normal Outrigger condition. The Ballasted Outrigger trace starts at 0.1 Hz and has a value of 0.180 degree/second/degree. The solid line remains fairly flat until 0.2 Hz where it begins to rise to a small peak of 0.2 degree/second/degree at 2.9 Hz. This line then falls to a low of 0.160 at 0.4 Hz, and remains fairly flat before rising to the last peak of 0.175 at 0.72 Hz. The trace then falls off to 0.150 at 2 Hz. The No Outrigger trace starts at 0.1 Hz and has a value of 0.165 degree/second/degree and remains fairly flat for the entire frequency range. The Normal Outrigger trace begins at 0.15 degree/second/degree at .1 Hz and rises to 0.175 at .3 Hz. The trace then goes through a few slight undulations in a narrow range of 0.16 to 0.17 degree/second/degree.

Figure 9.1: Vehicle Speed and Handwheel Angle Traces for 4Runner Low and Full Fuel Level Matched Tests 93 and 231

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Vehicle Speed in mph and Handwheel Angle in degrees. The top pane has a range of 0 to 45 mph in 5-mph increments and the bottom pane has a range of –400 to +800 degrees in 200-degree increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 10 seconds in 1-second increments.

The upper pane has two traces. The solid line represents the measured Vehicle Speed for Test 93 with a low Fuel Level, and the dash-dot line represents the Vehicle Speed for Test 231 with a High Fuel Level. The solid trace begins at approximately 38 mph and remains relatively flat for the first second. It then slowly drops to 35 mph at 2 seconds, and then drops more rapidly to approximately 15 mph at 5.5 seconds where the line again remains relatively flat until the 8 seconds where it starts to ascend and reaches 19 mph at 10 seconds. The broken line begins in the same manner for the first 2 seconds, but descends begins a little than the first trace. The speed drops from 35 mph at 2 seconds to 20 mph at 5 seconds. The line remains relatively flat from this point on.

The lower pane has two traces that represent the measured Handwheel Angle for Test 93 (Low Fuel Level) and Test 231 (High Fuel Level). The solid trace (Test 93) begins at the origin and remains flat for only a fraction of a second until falling quickly to –270 degrees at 0.5 second where the line remains flat until about 1.2 seconds. The trace then rises sharply to +700 degrees at 2 seconds and remains flat until 5 seconds. The trace then falls down to 200 degrees at 6 seconds and falls slightly down to 0 degrees at 7 seconds where it remains flat for the duration of the test. The dash-dot line for Test 231 follows the same pattern. The minor differences occur during the steering reversals with Test 231 rising more slowly on the ascent from –270 to 700 degrees (only from 200 to 700 degrees is the difference noticeable) and on the descent from 700 degrees to 0 degrees which begins slightly sooner for Test 231.

Figure 9.2: Corrected Lateral Acceleration and Roll Angle Traces for Two Similar Vehicle Speed Trace Tests – Driver A

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Corrected Lateral Acceleration in g's and Roll Angle in degrees. The top pane has a range of –1 to +1 g in 0.5-g increments and the bottom pane has a range of -10 to +10 degrees in 5-degree increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 10 seconds in 1-second increments.

The upper pane has two traces that represent the Corrected Lateral Acceleration for Tests 93 (Low Fuel Level) and 231 (High Fuel Level). Driver C conducted both of these tests. Both traces start at the origin and remain flat for only a fraction of a second. The traces then fall sharply to approximately –0.65 g at 1 second. For both traces, the response remains flat for about 0.3 seconds before rising sharply at 1.5 seconds from -0.65 g to 0.65 g at 2 seconds. For both traces, the response following this initial positive peak is oscillatory until approximately 5.5 seconds. The traces then return to 0 g at 6.5 seconds and remain relatively flat until the end of the time history.

The lower pane also has two traces that represent the Roll Angle for Tests 93 and 231. Both traces start near the origin and remain flat until approximately 0.5 seconds and then increase sharply to approximately 7 degrees near 0.9 seconds. The traces remains at this level until 1.5 seconds before falling to –7.5 degrees at 2 seconds. As was the case in the upper pane, the two traces have an oscillatory response until 5.5 seconds and then the traces return to 0 degrees at 7 seconds and remain relatively flat until the end of the time history.

Figure 10.1: Pulse Brake Duration as a Function of Pulse Brake Magnitude

This figure is an x-y scatter graph with individual points representing the Pulse Brake Duration for individual tests. The Pulse Brake durations are plotted as a function of Pulse Brake Magnitude. The y-axis is labeled Pulse Brake Duration and has units of seconds. The y-axis range is 0.15 to 0.45 seconds with 0.5-second increments. The x-axis is labeled Pulse Brake Duration and has units of pounds-force. The x-axis range is 0 to 300 pounds-force with 50-pound-force increments.

The individual data points are represented by triangles for Left steer tests (9 data points) and squares for Right steer tests (7 data points). Three linear regression of this data have been made and are presented in the figure. Left Fit is a dotted line that is a linear regression of the Left steer data, Right Fit is a thin solid line that is a linear regression of the Right steer data, and Fit All is a thick solid line that is a linear regression of all the data. The slope values are respectively for the Left Fit, Right Fit, and Fit All linear regressions: 1.02×10^{-3}, 0.86×10^{-3}, and 0.97×10^{-3} seconds/pound-force. The corresponding r^2 values are 0.94, 0.83, and 0.90.

Figure 10.2: Peak Deceleration due to Turn and Pulse Brake as a Function of Pulse Brake Magnitude

This figure is an x-y scatter graph with individual points representing Deceleration due to Turn and Brake for individual tests. The deceleration values are plotted as a function of Pulse Brake Magnitude. The y-axis is labeled Pulse Brake Deceleration and is in units of g. The y-axis range is 0.30 to 1.00 seconds with 0.1-second increments. The x-axis is labeled Pulse Brake Magnitude and has units of pounds-force. The x-axis range is 0 to 300 pounds-force with 50-pound-force increments.

The Deceleration increases with increasing Pulse Brake Magnitude. The individual data points are represented by triangles for Left steer tests (9 data points) and squares for Right steer tests (7 data points). Three linear regression of this data have been made and are presented in the figure. Left Fit is a dotted line that is a linear regression of the Left steer data, Right Fit is a thin solid line that is a linear regression of the Right steer data, and Fit All is a thick solid line that is a linear regression of all the data. The slope values are respectively for the Left Fit, Right Fit, and Fit All linear regressions: 2.33×10^{-3}, 1.53×10^{-3}, and 2.10×10^{-3} g/pound-force. The corresponding r^2 values are 0.93, 0.93, and 0.91.

Figure 10.3 – Roll Angle Dip due to Pulse Brake as a Function of Pulse Brake Magnitude

This figure is an x-y scatter graph with individual points representing Roll Angle Dip for individual tests. The Roll Angle Dip values are plotted as a function of Pulse Brake Magnitude. The y-axis is labeled Roll Angle Dip and is in units of degrees. The y-axis range is 4.50 to 7.50 degrees with 0.5-degree increments. The x-axis is labeled Pulse Brake Magnitude and has units of pounds-force. The x-axis range is 0 to 300 pounds-force with 50-pound-force increments.

The Roll Angle Dip decreases with increasing Pulse Brake Magnitude. The individual data points are represented by triangles for Left steer tests (9 data points) and squares for Right steer tests (7 data points). Three linear regression of this data have been made and are presented in the figure. Left Fit is a dotted line that is a linear regression of the Left steer data, Right Fit is a thin solid line that is a linear regression of the Right steer data, and Fit All is a thick solid line that is a linear regression of all the data. The slope values are respectively for the Left Fit, Right Fit, and Fit All linear regressions: -0.69×10^{-2}, -1.24×10^{-2}, and -0.87×10^{-2} degrees/pound-force. The corresponding r^2 values are 0.69, 0.89, and 0.71.

Figure 10.4: Peak Roll Angle Post-Pulse Brake as a Function of Pulse Brake Magnitude

This figure is an x-y scatter graph with individual points representing Peak Roll Angle Post-Pulse for individual tests. The Peak Roll Angle Post-Pulse values are plotted as a function of Pulse Brake Magnitude. The y-axis is labeled Peak Roll Angle Post-Pulse and is in units of degrees. The y-axis range is 7.50 to 10.0 degrees with 0.5-degree increments. The x-axis is labeled Pulse Brake Magnitude and has units of pounds-force. The x-axis range is 0 to 300 pounds-force with 50-pound-force increments.

The Peak Roll Angle Post-Pulse increases with increasing Pulse Brake Magnitude. The individual data points are represented by triangles for Left steer tests (9 data points) and squares for Right steer tests (7 data points). Three linear regression of this data have been made and are presented in the figure. Left Fit is a dotted line that is a linear regression of the Left steer data, Right Fit is a thin solid line that is a linear regression of the Right steer data, and Fit All is a thick solid line that is a linear regression of all the data. The slope values are respectively for the Left Fit, Right Fit, and Fit All linear regressions: 1.04×10^{-2}, 0.45×10^{-2}, and 0.87×10^{-2} degrees/pound-force. The corresponding r^2 values are 0.77, 0.46, and 0.61.

Figure 10.5: Corrected Lateral Acceleration Dip Due to Pulse Brake as a Function of Pulse Brake Magnitude

This figure is an x-y scatter graph with individual points representing Corrected Lateral Acceleration Dip Due to Pulse Brake for individual tests. The Corrected Lateral Acceleration Dip Due to Pulse Brake values are plotted as a function of Pulse Brake Magnitude. The y-axis is labeled Corrected Lateral Acceleration Dip in units of g. The y-axis range is 0.50 to 0.85 g with 0.05-g increments. The x-axis is labeled Pulse Brake Magnitude and has units of pounds-force. The x-axis range is 0 to 300 pounds-force with 50-pound-force increments.

The Corrected Lateral Acceleration Dip Due to Pulse Brake decreases with increasing Pulse Brake Magnitude. The individual data points are represented by triangles for Left steer tests (9 data points) and squares for Right steer tests (7 data points). Three linear regression of this data have been made and are presented in the figure. Left Fit is a dotted line that is a linear regression of the Left steer data, Right Fit is a thin solid line that is a linear regression of the Right steer data, and Fit All is a thick solid line that is a linear regression of all the data. The slope values are respectively for the Left Fit, Right Fit, and Fit All linear regressions: $-.84 \times 10^{-3}$, -1.17×10^{-3}, and -0.96×10^{-3} g/pound-force. The corresponding r^2 values are 0.80, 0.92, and 0.64.

Figure 10.6: Peak Corrected Lateral Acceleration Post-Pulse Brake as a Function of Pulse Brake Magnitude

This figure is an x-y scatter graph with individual points representing Peak Corrected Lateral Acceleration Post-Pulse Brake for individual tests. The Peak Corrected Lateral Acceleration Post-Pulse Brake values are plotted as a function of Pulse Brake Magnitude. The y-axis is labeled Peak Corrected Lateral Acceleration Post-Pulse in units of g. The y-axis range is 0.80 to 0.96 g with 0.02-g increments. The x-axis is labeled Pulse Brake Magnitude and has units of pounds-force. The x-axis range is 0 to 300 pounds-force with 50-pound-force increments.

The Peak Corrected Lateral Acceleration Post-Pulse values are quite scattered. The individual data points are represented by triangles for Left steer tests (9 data points) and squares for Right steer tests (7 data points). Three linear regression of this data have been made and are presented in the figure. Left Fit is a dotted line that is a linear regression of the Left steer data, Right Fit is a thin solid line that is a linear regression of the Right steer data, and Fit All is a thick solid line that is a linear regression of all the data. The slope values are respectively for the Left Fit, Right Fit, and Fit All linear regressions: 2.37×10^{-4}, -2.08×10^{-4}, and 1.00×10^{-4} g/pounds-force. The corresponding r^2 values are 0.41, 0.09, and 0.04.

Figure 10.7: Comparison of Toyota 4Runner J-Turn with Pulse Brake Using the Steering Controller – Tests 369 and 371 - Corrected Lateral Acceleration

This figure has a single pane with Corrected Lateral Acceleration in g on the y-axis and Time in seconds on the x-axis. The y-axis has a range of –0.1 to 1 g in 0.1-g increments and the x-axis has a range of 0 to 6 seconds in 1-second increments. This figure has two traces that represent the Corrected Lateral Acceleration for Tests 369 (solid line) and 371 (dotted line). Both traces begin near the origin and remain flat until 0.7 seconds before rising rapidly to an initial peak at 0.77 g at 1.3 seconds. The traces are very similar up to this point, but then separate due primarily to the timing of the pulse brake. The pulse brake for Test 369 occurs approximately 0.3 seconds later than it does for Test 371. The trace for

369 remains relatively flat for another 0.2 g after the initial 0.77 g peak and then rises to 0.81 g near 1.9 seconds. The trace then falls sharply to approximately 0.55 g at 2 seconds (due to the pulse brake). This trace then rise to 0.8 g at 2.5 seconds and this is followed by three more oscillations with peaks of 0.81 g at 3 seconds, 0.80 g at 3.5 seconds and 0.7 g at 4 seconds. The trace then drops smoothly to 0.5 g at 6 seconds. The trace for Test 371 drops to 0.63 g at 1.85 seconds which is much sooner than the drop for Test 369, but not as deep a drop. The trace then rises back up to about 0.79 g at 2 seconds. The trace then has 4 peaks of 0.81 g at 2.2 seconds, 0.86 at 2.7 seconds, 0.91 g at 3.3 seconds, and 0.9 g at 4.1 seconds. The trace falls relatively rapidly to –0.1 g near 4.9 seconds and oscillates between –0.1 and 0 g until the trace ends at 6 seconds.

Figure 10.8: Roll Rate Dip Due to Pulse Brake as a Function of Pulse Brake Magnitude

This figure is an x-y scatter graph with individual points representing Roll Rate Dips due to Pulse Brakes for individual tests. The Roll Rate Dips are plotted as a function of Pulse Brake Magnitude. The y-axis is labeled Roll Rate Dip and is in units of degree/second. The y-axis range is 0.00 to 14 degree/second with 2-degree/second increments. The x-axis is labeled Pulse Brake Magnitude and has units of pounds-force. The x-axis range is 0 to 300 pounds-force with 50-pound-force increments.

The Roll Rate Dip Due to Pulse Brake values are quite scattered. The individual data points are represented by triangles for Left steer tests (9 data points) and squares for Right steer tests (7 data points). Three linear regression of this data have been made and are presented in the figure. Left Fit is a dotted line that is a linear regression of the Left steer data, Right Fit is a thin solid line that is a linear regression of the Right steer data, and Fit All is a thick solid line that is a linear regression of all the data. The slope values are respectively for the Left Fit, Right Fit, and Fit All linear regressions: 1.57×10^{-2}, 3.94×10^{-2}, and 2.35×10^{-2} degree/second/pounds-force. The corresponding r^2 values are 0.13, 0.57, and 0.23.

Figure 10.9: Peak Roll Rate Post- Pulse Brake as a Function of Pulse Brake Magnitude

This figure is an x-y scatter graph with individual points representing Peak Roll Rate Post-Pulse Brake values for individual tests. The Roll Rate Dips are plotted as a function of Pulse Brake Magnitude. The y-axis is labeled Roll Rate Dip and has units of degree/second. The y-axis range is 0.00 to 14 degree/second with 2-degree/second increments. The x-axis is labeled Pulse Brake Magnitude and has units of pounds-force. The x-axis range is 0 to 300 pounds-force with 50-pound-force increments.

The Peak Roll Rate Post-Pulse Brake values generally increase with increasing Pulse Brake Magnitude. The individual data points are represented by triangles for Left steer tests (9 data points) and squares for Right steer tests (7 data points). Three linear regression of this data have been made and are presented in the figure. Left Fit is a dotted line that is a linear regression of the Left steer data, Right Fit is a thin solid line that is a linear regression of the Right steer data, and Fit All is a thick solid line that is a linear regression of all the data. The slope values are respectively for the Left Fit, Right Fit, and Fit All linear regressions: 6.76×10^{-2}, 5.53×10^{-2}, and 6.52×10^{-2} pounds-force. The corresponding r^2 values are 0.80, 0.65, and 0.59.

Figure 10.10: The Effect of Pulse Brake Timing on Roll Rate Response

This figure contains 2 subplots or “panes”. The top and bottom pane y-axis labels are, respectively, Brake Pedal Force in pounds-force and Roll Rate in degrees/second. The top pane has a range of –20 to +120 pounds-force in 20-degree increments and the bottom pane has a range of -30 to 30 degrees/second in 10-degree/second increments. The x-axis is labeled Time in seconds (for both panes) and has a range of 0 to 6 seconds in 1-second increments.

The upper pane has two traces that represent the measured Brake Pedal Force for Tests 372 (solid line) and 375 (dotted line). Both traces start near the origin and remain flat until approximately 3.1 seconds for Test 375 and 3.3 seconds for Test 372. The traces then rise rapidly to 117 pounds-force at 3.2 seconds for Test 372 and 112 pounds-force at 3.4 seconds for Test 375. The traces fall sharply back to zero by 3.3 seconds for Test 375 and 3.6 seconds for Test 372. The traces remain flat for the duration of the time history.

The lower pane also has two traces that represent the measured Roll Rate for Tests 372 and 375. The two traces are nearly identical up to the point of the brake application. Both traces start near the origin and remain relatively flat until the 2.5 second mark, where they start to fall rapidly down to –28 degrees/second at 2.8 seconds. They then rise back up to the first positive peak of 5 degrees/second at 3 seconds. The braking onsets are noted on the downward slope after this peak for each test. For Test 372, the braking onset is marked with a plus sign at 3.3 seconds and –8 degrees/second, while for Test 375, the braking onset is marked with a circle at 3.1 seconds and –2 degrees/second. Both traces reverse direction shortly after the braking onset and have multiple oscillations. The peaks for Test 372 are 10 degrees/second at 3.6 seconds, 12 degrees/second at 4.2 seconds, 12 degrees/second at 5 seconds, and 18 degrees/second at 6 seconds. For Test 375 the peaks are 4 degrees/second at 3.4 seconds, 5 degrees/second at 3.9 seconds, 6 degrees/second at 4.4 seconds, 10 degrees/second at 5 seconds, and 20 degrees/second at 5.6 seconds.

Figure 10.11: Yaw Rate Dip Due to Pulse Brake as a Function of Pulse Brake Magnitude

This figure is an x-y scatter graph with individual points representing Yaw Rate Dips due to Pulse Brake for individual tests. The Yaw Rate Dips are plotted as a function of Pulse Brake Magnitude. The y-axis is labeled Yaw Rate Dip and has units of degree/second. The y-axis range is 15 to 35 degree/second with 2-degree/second increments. The x-axis is labeled Pulse Brake Magnitude and has units of pounds-force. The x-axis range is 0 to 300 pounds-force with 50-pound-force increments.

The Yaw Rate Dip Due to Pulse Brake values are quite scattered. The individual data points are represented by triangles for Left steer tests (9 data points) and squares for Right steer tests (7 data points). Three linear regression of this data have been made and are presented in the figure. Left Fit is a dotted line that is a linear regression of the Left steer data, Right Fit is a thin solid line that is a linear regression of the Right steer data, and Fit All is a thick solid line that is a linear regression of all the data. The slope values are respectively for the Left Fit, Right Fit, and Fit All linear regressions: -9.79×10^{-3}, 0.23×10^{-3}, and -2.73×10^{-3} pounds-force. The corresponding r^2 values are 0.01, 0.83, and 0.11.

Figure 10.12: J-Turn Steering Inputs using the Steering Controller

The Handwheel Angle traces for 4 Runner J-Turn Tests 345-353 are plotted in this figure. The y-axis is labeled Handwheel Angle in degrees and has a range of –350 to +50 degrees in 50-degree increments. The x-axis is labeled Time in seconds and has a range of 0 to 7 seconds in whole second increments. There is very little difference in the traces up to the point where the driver takes control back from the steering controller. All of the traces start near the origin and remain relatively flat until 1 second where they drop rapidly to –330 degrees at 1.33 seconds. All of the traces remain at this level until 3.5 seconds or later. The traces then return towards zero degrees as the driver takes control back from the steering controller. The traces start the return to 0-degrees as early as 3.5 seconds and as late as 5 seconds.

Figure 10.13: Fishhook Repeatability Tests with the Steering Controller - Handwheel Angle and Vehicle Speed

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Handwheel Angle in degrees and Vehicle Speed in mph. The top pane has a range of –600 to +250 degrees in 50-degree increments and the bottom pane has a range of 0 to 40 mph in 10-mph increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 8 seconds in 1-second increments.

The upper pane has four traces that represent the measured Handwheel Angle for Tests 262, 268, 106, and 117. All of the traces start at the origin and remain flat until approximately 1.0 second. The traces then rise sharply to +270 degrees at 1.3 seconds. The traces remain flat at this level until approximately 1.8 seconds where they fall to –600 degrees. They remain flat at this level until 6 seconds before returning back to 0 degrees at 7 seconds. They stay at 0 degrees for the remainder of the time history.

The lower pane also has four traces that represent the measured Vehicle Speed for tests 262, 268, 106, and 117. The traces are nearly identical for the entire time history. They begin at approximately 30 mph and remain relatively flat until the 1.5 second mark, where they start to fall off gradually. By 2 seconds, the vehicle speed is 28 mph, 3 seconds - 25 mph, 4 seconds - 19 mph, and 6 seconds - 12 mph. The traces remain at this level for the duration of the time history.

Figure 10.14: Fishhook Repeatability Tests with Steering Controller - Corrected Lateral Acceleration and Roll Angle

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Corrected Lateral Acceleration in g and Roll Angle in degrees. The top pane has a range of –1 to +1 g in 0.5-g increments and the bottom pane has a range of -10 to 10 degrees in 5-degree increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 8 seconds in 1 second increments.

The upper pane has four traces that represent the Corrected Lateral Acceleration for Tests 262, 268, 106, and 117. Both traces start near the origin and remain flat until approximately 1 second. The traces then rise to approximately +0.75 g at 1.8 seconds. For all traces, the response following this initial positive peak is oscillatory with four negative peaks ranging from approximately –0.6 to –0.8 g. The traces are fairly flat after these peaks at -0.6 g until 6 seconds where they rise to -0.5 g and then at 7 seconds to +0.1 g.

The lower pane also has four traces that represent the Roll Angle for Tests 262, 268, 106, and 117. All traces start near the origin and remain flat until approximately 1.0 seconds and then drop sharply to approximately -7 degrees near 1.3 seconds. The lines begin to rise sharply at 2 seconds where several peaks are formed at 2.8, 3.2, 3.7, 4.2, and 4.9 seconds. These peaks are about 8 degrees in magnitude. At 5 seconds the traces levels off to 5 degrees before falling down to –1 deg at 7.2 seconds.

Figure 10.15: Fishhook Repeatability Tests with Steering Controller – Roll Velocity and Yaw Velocity

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Roll Velocity in degree/second and Yaw Velocity in degree/second. The top pane has a range of –-40 to +40 g in10-degree/second increments and the bottom pane has a range of -60 to +40 degree/second in 20-degree/second increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 8 seconds in 1-second increments.

The upper pane has four traces that represent the Corrected Lateral Acceleration for Tests 262, 268, 106, and 117. All of these traces are very similar. This is especially true for the first 3 seconds. There are some differences as the vehicles go through small oscillations after the 3-second point. All traces start near the origin and remain flat until approximately 1.0 second. The traces then fall sharply to approximately –22 deg/sec at 1.1 second. For all traces, the response following this initial negative peak is oscillatory with positive peaks ranging from approximately 35 to 10 deg/sec. The largest positive peak occurs on the first oscillation for all tests at 2.3 seconds at 35 deg/sec, with the four lesser peaks following. The oscillatory response ends by 5.5 seconds.

The lower pane also has four traces that represent the Yaw Velocity for Tests 262, 268, 106, and 117. All traces start at the origin and remain flat until approximately 1.0 second and then increase sharply to approximately 30 degrees/second near 1.4 seconds. This peak lasts until approximately the 2-second point, where the traces then reverse direction reach approximately –35 degrees/second at 2.8 seconds. The traces have small undulations, but generally tend to decrease reaching –50 degrees/second at 6 seconds. At this point, the traces increase back up reach 0 degrees/second at 7.2 second and staying relatively flat until the end of the time history at 8 seconds.

Figure 10.16: Comparison of Left and Right Steer, 0.2 Second Pulse Duration, and 40 mph Frequency Response Curves – Corrected Lateral Acceleration

This figure has two sub-plots or "panes". The x-axis is "Frequency in Hertz" from 0.1 Hz to 10 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axes are labeled Magnitude and Phase Angle from top to bottom. The Magnitude scale has units of g/degree and ranges from 0 to 8 x 10^{-3}. The Phase Angle scale has units of degrees and ranges from –400 to 0 degrees.

The Phase Angle pane also has two traces: one solid line that represents the left steer Test 71 and one dashed line that represents the right steer Test 75. These traces are very similar to each other. Both traces start at 0.2 Hz and -10 degrees. The traces then fall to -70 degrees by 1.0 Hz. They then fall more rapidly to –300 degrees at 2 Hz and –400 degrees at 4 Hz.

The Magnitude pane has two traces: one solid line that represents the left steer Test 71, and one dashed line that represents the right steer Test 75. The solid line starts at 0.2 Hz and has a value of 5 x 10^{-3}

g/degree. The trace remains relatively flat until 0.8 Hz. It then decreases to 0.4 x 10^{-3} g/degree at 1.8 Hz and then rises to 4 x 10^{-3} g/degree and 4.0 Hz. The dashed line has a similar shape, but starts at a higher level (5.8 x 10^{-3} g/degree). This trace merges with the solid line near 1.3 seconds.

Figure 10.17: Comparison of Left and Right Steer, 0.2 Second Pulse Duration, and 40 mph Frequency Response Curves – Roll Angle

This figure has two sub-plots or "panes". The x-axis is "Frequency in Hertz" from 0.1 Hz to 10 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axes are labeled Magnitude and Phase Angle from top to bottom. The Magnitude scale has units of degree/degree and ranges from 0 to 0.08. The Phase Angle scale has units of degrees and ranges from –50 to 200 degrees.

The Phase Angle pane has two traces: one solid line that represents the left steer Test 71 and one dashed line that represents the right steer Test 75. These two traces have a very similar shape. The solid line starts at 0.2 Hz and 170 degrees. This trace slowly ramps down to 35 degrees at 1.8 Hz then rises to a small peak at 60 degrees at 2 Hz where it then drops to –30 degrees at 4 Hz. The dashed line has the same basic shape and begins 10 degrees below the solid line and becomes indiscernible from the solid line from 1.0 to 1.8 Hz. This trace reaches a higher peak (70 degrees) at the 2 Hz point, but is again barely discernable from the solid line beyond 2.4 Hz.

The Magnitude pane has two traces: one solid line that represents the left steer Test 71, and one dashed line that represents the right steer Test 75. These two traces have the same basic shape. The solid line starts at 0.20 Hz and has a value of 0.041 degree/degree. This trace rises slightly to 0.042 at 0.8 Hz. It then ramps down to 0.012 degree/degree at 1.8 Hz. It then rises to a small peak of 0.018 at 2.7 Hz before falling to 0.008 at 4.0 Hz. The right steer trace has the same basic shape but begins 0.01 degree/degree above the left steer trace (0.051 deg/deg). This right steer trace also begins to fall at 0.8 Hz and the two lines are barely discernible beyond 1.8 Hz.

Figure 10.18: Comparison of Left and Right Steer, 0.2 Second Pulse Duration, and 40 mph Frequency Response Curves – Roll Rate

This figure has two sub-plots or "panes". The x-axis is "Frequency in Hertz" from 0.1 Hz to 10 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axes are labeled Magnitude and Phase Angle from top to bottom. The Magnitude scale has units of degree/second/degree and ranges from 0 to 0.3. The Phase Angle scale has units of degrees and ranges from –400 to 0 degrees.

The Phase Angle pane has two traces: one solid line that represents the left steer of Test 71 and one dashed line that represents the right steer Test 75. Both traces have the same basic shape and become barely discernible beyond 0.6 Hz. The solid line starts at 0.2 Hz and has a value of -105 degrees. The trace slowly ramps down to -240 degrees at 1.7 Hz then rises to -215 degrees at 2 Hz. The trace then decreases to –330 degrees at 4 Hz. The dashed line starts approximately 10 degrees below the solid line, but is barely discernible from the solid line by 0.6 Hz.

The Magnitude pane has two traces: one solid line that represents the left steer Test 71, and one dashed line that represents the right steer of Test 75. These two traces have the same basic shape. The solid line starts at 0.2 Hz and has a value of 0.05 degree/second/degree. The trace increases to 0.26 at 1.3 Hz and then falls to 0.13 at 1.8 Hz. The trace then rises to a second peak of 0.28 at 2.8 Hz and then falls to 0.23

at 4 Hz. The dashed line starts at 0.06, rises to 0.275 at 1 Hz, drops to 0.13 at 1.8 Hz and is then barely discernable from the solid line beyond this point.

Figure 10.19: Comparison of Left and Right Steer, 0.2 Second Pulse Duration, and 40 mph Frequency Response Curves – Yaw Rate

This figure has two sub-plots or "panes". The x-axis is "Frequency in Hertz" from 0.01 Hz to 10 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axes are labeled Magnitude and Phase Angle from top to bottom. The Magnitude scale has units of degree/second/degree and ranges from 0 to 0.3. The Phase Angle scale has units of degrees and ranges from –200 to 0 degrees.

The Phase Angle pane has two traces: one solid line that represents the left steer of Test 71 and one dashed line that represents the right steer of Test 75. Both traces have a very similar shape. Both start at 0.2 Hz and -10 degrees. The traces slowly decrease to -40 degrees at 1.0 Hz then more rapidly to -170 degrees at 4 Hz.

The Magnitude pane has two traces: one solid line that represents the left steer of Test 71, and one dashed line that represents the right steer of Test 75. The traces have a similar shape, but the magnitude for Test 75 is higher at lower frequencies. The solid line, Test 71, starts at 0.2 Hz and has a value of 0.14 degree/second/degree. The trace remains relatively flat until 0.6 Hz where it then starts to rise reaching a peak of 0.175 at 1.5 Hz and then drops to 0.06 at 4.0 Hz. The dashed line has the same basic shape but begins approximately 0.03 degree/second/degree above the solid line at the beginning of the trace and becomes barely discernible from the left steer trace by 1.8 Hz.

Figure 10.20: Comparison of Left Steer, 0.2 and 0.3 Second Pulse Duration, and 40 mph Frequency Response Curves – Corrected Lateral Acceleration

This figure has two sub-plots or "panes". The x-axis is "Frequency in Hertz" from 0.01 Hz to 10 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axes are labeled Magnitude and Phase Angle from top to bottom. The Magnitude scale has units of g/degree and ranges from 0 to $8x10^{-3}$. The Phase Angle scale has units of degrees and ranges from –400 to 0 degrees.

The Phase Angle pane has two traces: one solid line that represents the left steer Test 71 (0.2 Second Pulse, 40 mph) and one dashed line that represents the left steer Test 79 (0.3 Second Pulse, 40 mph). The two traces are very similar. Both traces start at 0.2 Hz and have a value of -10 degrees. They slowly decrease to -100 degrees at 1.3 Hz then more rapidly to -325 degrees at 2 Hz. The traces then decrease less rapidly to –400 degrees at 4 Hz.

The Magnitude pane has two traces: one solid line that represents the left steer Test 71, and one dashed line that represents the left steer trace Test 79. The two traces have a very similar shape. The solid line starts at 0.2 Hz and has a value of $5x10^{-3}$ g/deg. The trace remains flat until 0.8 Hz where it starts to decrease reaching 0.5×10^{-3} g/deg at 1.8 Hz. The trace then increases to 3.9×10^{-3} g/degree at 4.0 Hz. The dashed line has the same basic shape and is approximately 0.3×10^{-3} above the solid line at the beginning of the trace and becomes barely discernible from it by 1.0 Hz.

Figure 10.21: Comparison of Left Steer, 0.2 and 0.3 Second Pulse Duration, and 40 mph Frequency Response Curves – Roll Angle

This figure has two sub-plots or "panes". The x-axis is "Frequency in Hertz" from 0.01 Hz to 10 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axes are labeled Magnitude and Phase Angle from top to bottom. The Magnitude scale has units of degree/degree and ranges from 0 to 0.08. The Phase Angle scale has units of degrees and ranges from –50 to 200 degrees.

The Phase Angle pane has two traces: one solid line that represents the left steer Test 71 (0.2 Second Pulse, 40 mph) and one dashed line that represents the left steer Test 79 (0.3 Second Pulse, 40 mph). The two traces are barely discernible from each other. Both traces start at 0.2 Hz and have a value of 170 degrees. The trace slowly ramps down to 90 degrees at 1 Hz and then 35 degrees at 1.7 Hz. They then rise to a peak of 60 degrees at 2 Hz before falling to –30 degrees at 4 Hz.

The Magnitude pane has two traces: one solid line that represents the left steer trace Test 71, and one dashed line that represents the left steer Test 79. The two traces are barely discernible from each other. Both traces start at 0.20 Hz and 0.042 degree/degree. The traces then rise only slightly to 0.044 degree/degree at 0.8 Hz before falling to 0.013 deg/deg at 1.8 Hz. The traces then rise to 0.018 at 2.7 Hz and then drop back to 0.013 at 4 Hz.

Figure 10.22: Comparison of Left Steer, 0.2 and 0.3 Second Pulse Duration, and 40 mph Frequency Response Curves – Roll Rate

This figure has two sub-plots or "panes". The x-axis is "Frequency in Hertz" from 0.01 Hz to 10 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axes are labeled Magnitude and Phase Angle from top to bottom. The Magnitude scale has units of degree/second/degree and ranges from 0 to 0.3. The Phase Angle scale has units of degrees and ranges from –400 to 0 degrees.

The Phase Angle pane has two traces: one solid line that represents the left steer Test 71 (0.2 Second Pulse, 40 mph) and one dashed line that represents the left steer Test 79 (0.3 Second Pulse, 40 mph). Except for the very beginning, the two traces are barely discernable from each other. Both traces start at 0.2 Hz, but the solid line has an initial value of -100 degrees and the dashed line has an initial value of -120 degrees. Both traces have a value of –120 degrees at 0.4 Hz. The traces then slowly ramp down to -230 degrees at 1.7 Hz, rise to a small peak of -220 degrees and 2 Hz, and then fall to –320 at 4 Hz.

The Magnitude pane has two traces: one solid line that represents the left steer trace Test 71 (0.2 Second Pulse, 40 mph) and one dashed line that represents the left steer Test 79 (0.3 Second Pulse, 40 mph). These two traces have the same basic shape. Test 71 starts at 0.20 Hz and has a value of 0.05 degree/second/degree. The trace then rises to 0.26 degree/second/degree at 1.3 Hz. The dashed line is slightly above the solid line over this range. The solid line then falls to 0.13 at 1.8 Hz with the dashed line being slightly below over this range. This solid line then increases to 0.28 at 2.9 Hz and then drops to 0.23 at 4 Hz. The dashed line is slightly above the solid line over this range.

Figure 10.23: Comparison of Left Steer, 0.2 and 0.3 Second Pulse Duration, and 40 mph Frequency Response Curves – Yaw Rate

This figure has two sub-plots or "panes". The x-axis is "Frequency in Hertz" from 0.01 Hz to 10 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axes are labeled Magnitude and Phase Angle from top to bottom. The Magnitude scale has units of degree/second/degree and ranges from 0 to 0.3. The Phase Angle scale has units of degrees and ranges from –200 to 0 degrees.

The Phase Angle pane has two traces: one solid line that represents the left steer Test 71 (0.2 Second Pulse, 40 mph) and one dashed line that represents the left steer Test 79 (0.3 Second Pulse, 40 mph). The two traces are barely discernable from each other. The traces start at 0.20 Hz and have a value of -10 degrees. The traces slowly ramp down to -40 degrees at 1.0 Hz and then decrease more rapidly to -170 degrees at 4 Hz.

The Magnitude pane has two traces: one solid line that represents the left steer Test 71 (0.2 Second Pulse, 40 mph) and one dashed line that represents the left steer Test 79 (0.3 Second Pulse, 40 mph). The two traces are very similar. The solid line starts at 0.20 Hz and has a value of 0.14 degree/second/degree. The trace then rises to 0.175 at 1.4 Hz. The dashed line is slightly higher over this range. The solid line then drops to 0.1 at 2.3 Hz with the dashed line being slightly lower over this range. The solid line then drops further to 0.06 at 4.0 Hz with the dashed line being slightly higher over this range.

Figure 10.24: Comparison of Left Steer, 0.2 Second Pulse Duration, and 40 and 50 mph Frequency Response Curves – Corrected Lateral Acceleration

This figure has two sub-plots or "panes". The x-axis is "Frequency in Hertz" from 0.01 Hz to 10 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axes are labeled Magnitude and Phase Angle from top to bottom. The Magnitude scale has units of g/degree and ranges from 0 to 10×10^{-3} g/deg. The Phase Angle scale has units of degrees and ranges from –400 to 0 degrees.

The Phase Angle pane has two traces: one solid line that represents the left steer Test 71 (0.2 Second Pulse, 40 mph) and one dashed line that represents the left steer Test 87 (0.2 Second Pulse, 50 mph). The dashed line has the same basic shape as the solid line, but is generally a few degrees below the solid line. The solid line starts at 0.20 Hz and has a value of -10 degrees. The trace slowly ramps down to -100 degrees at 1.3 Hz then more rapidly to -325 degrees at 2.2 Hz. It then decreases less rapidly to –400 degrees at 4 Hz.

The Magnitude pane has two traces: one solid line that represents the left steer Test 71 (0.2 Second Pulse, 40 mph) and one dashed line that represents the left steer Test 87 (0.2 Second Pulse, 50 mph). The two traces have the same basic shape, but the dashed line is higher than the solid line for lower frequencies. Both traces are relatively flat from 0.2 to 0.8 Hz with the solid line having a magnitude of 5×10^{-3} g/degree and the dashed line having a magnitude of 6.2×10^{-3} g/deg. Both traces then decrease and reach a trough of 0.5×10^{-3} g/deg at 1.8 Hz. They both then rise reaching a peak of 3.9×10^{-3} g/deg at 4 Hz.

Figure 10.25: Comparison of Left Steer, 0.2 Second Pulse Duration, and 40 and 50 mph Frequency Response Curves – Roll Angle

This figure has two sub-plots or “panes”. The x-axis is “Frequency in Hertz” from 0.01 Hz to 10 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axes are labeled Magnitude and Phase Angle from top to bottom. The Magnitude scale has units of deg/degree and ranges from 0 to 0.09 degree/degree. The Phase Angle scale has units of degrees and ranges from -50 to 200 degrees.

The Phase Angle pane has two traces: one solid line that represents the left steer Test 71 (0.2 Second Pulse, 40 mph) and one dashed line that represents the left steer Test 87 (0.2 Second Pulse, 50 mph). The two traces have the same basic shape. The solid line for Test 71 starts at 0.20 Hz and has a value of 170 degrees. The trace slowly ramps down to 120 degrees at 0.8 Hz and then down 35 degrees at 1.7 Hz. The dashed line is slightly lower over this range. The solid line then rises to a small peak of 60 degrees at 2.0 Hz before falling off to –30 degrees at 4.0 Hz. The dashed line reaches a slightly higher peak (70 degrees), but also drops to –30 degrees at 4.0 Hz.

The Magnitude pane has two traces: one solid line that represents the left steer trace Test 71 (0.2 Second Pulse, 40 mph) and one dashed line that represents the left steer Test 87 (0.2 Second Pulse, 50 mph). The two traces have the same basic shape. Both traces are relatively flat over the range of 0.2 to 0.8 Hz with the solid line having a magnitude of 0.04 degree/degree and the dashed line having a value of 0.055 degree/degree. Both traces then decrease to a trough at 1.9 Hz (0.012 and 0.009 degree/degree for the solid and dashed lines respectively), before rising to a slight peak of 0.018 at 2.5 Hz and then drop to 0.01 at 4 Hz.

Figure 10.26: Comparison of Left Steer, 0.2 Second Pulse Duration, and 40 and 50 mph Frequency Response Curves – Roll Rate

This figure has two sub-plots or “panes”. The x-axis is “Frequency in Hertz” from 0.01 Hz to 10 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axes are labeled Magnitude and Phase Angle from top to bottom. The Magnitude scale has units of degree/second/degree and ranges from 0 to 0.3. The Phase Angle scale has units of degrees and ranges from –400 to 0 degrees.

The Phase Angle pane has two traces: one solid line that represents the left steer Test 71 (0.2 Second Pulse, 40 mph) and one dashed line that represents the left steer Test 87 (0.2 Second Pulse, 50 mph). The solid and dashed lines are very similar. Both start at 0.20 Hz and have a value of -100 degrees. The lines ramps down to approximately -240 degrees at 1.7 Hz (the dashed line reaching a slightly lower level than the solid line), then rise to a small peak at -220 degrees at 2.0 Hz before falling to –320 degrees at 4.0 Hz.

The Magnitude pane has two traces: one solid line that represents the left steer Test 71 (0.2 Second Pulse, 40 mph) and one dashed line that represents the left steer Test 87 (0.2 Second Pulse, 50 mph). The two traces have a similar shape. The solid line starts at 0.20 Hz and has a value of .05 degree/second/degree. The trace then rises to 0.26 at 1.3 Hz before falling to 0.14 at 1.8 Hz. It then rises to 0.28 at 3 Hz and drops to 0.24 at 4 Hz. The dashed line starts at 0.07 degree/second/degree at 0.2 Hz, rises to 0.3 at 1.3 Hz, drops to 0.11 at 1.8 Hz and then closely follows the solid line beyond this point.

Figure 10.27: Comparison of Left Steer, 0.2 Second Pulse Duration, and 40 and 50 mph Frequency Response Curves – Yaw Rate

This figure has two sub-plots or “panes”. The x-axis is “Frequency in Hertz” from 0.01 Hz to 10 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axes are labeled Magnitude and Phase Angle from top to bottom. The Magnitude scale has units of degree/second/degree and ranges from 0 to 0.3. The Phase Angle scale has units of degrees and ranges from –200 to 0 degrees.

The Phase Angle pane has two traces: one solid line that represents the left steer Test 71 (0.2 Second Pulse, 40 mph) and one dashed line that represents the left steer Test 87 (0.2 Second Pulse, 50 mph). The two lines are very similar. Both start at 0.20 Hz and have a value of -10 degrees. The traces slowly ramps down to –40 degrees at 1 Hz, -100 degrees at 1.8 Hz, and -170 degrees at 4.0 Hz.

The Magnitude pane has two traces: one solid line that represents the left steer Test 71 (0.2 Second Pulse, 40 mph) and one dashed line that represents the left steer Test 87 (0.2 Second Pulse, 50 mph). The two traces have a similar shape. The solid line starts at 0.20 Hz and has a value of 0.145 degree/second/degree. The trace then rises to 0.15 at 0.8 Hz, and rises more rapidly to a rounded peak of 0.175 at 1.5 Hz. The trace then drops to 0.13 at 2 Hz, 0.08 at 3 Hz, and 0.06 at 4.0 Hz. The dashed line also begins at 0.145 degree/second/degree at 0.2 Hz. It rises to 0.16 at 0.5 Hz, and then rises more rapidly to a rounded peak of 0.21 at 1.3 Hz. The trace then drops down and coincides with the solid line for frequencies above 2 Hz.

Figure 10.28: Comparison of 40 mph, 0.1 to 1.0 and 0.1 to 2.5 Hertz Sinusoidal Sweep Frequency Response Curves – Corrected Lateral Acceleration

This figure has two sub-plots or “panes”. The x-axis is “Frequency in Hertz” from 0.01 Hz to 10 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axes are labeled Magnitude and Phase Angle from top to bottom. The Magnitude scale has units of g/degree and ranges from 0 to 0.012. The Phase Angle scale has units of degrees and ranges from –500 to 0 degrees. These figures are only discussed for the range 0.1 to 1 Hz since this is overlap in the frequency range for the two test procedures.

The Phase Angle pane has two traces: one solid line that represents Test 120 (0.1 to 2.5 Hz Sine Sweep, 40 mph) and one dashed line that represents Test 125 (0.1 to 1.0 Hz Sine Sweep, 40 mph). The two traces are nearly identical over the frequency range of interest. They start at 0 degrees and 0.1 Hz. They slowly drop to –15 degrees at 0.2 Hz, -20 at 0.4 Hz, -40 at 0.7 Hz, and –70 at 1 Hz.

The Magnitude pane has two traces: one solid line that represents Test 120 (0.1 to 2.5 Hz Sine Sweet, 40 mph) and one dashed line that represents Test 125 (0.1 to 1.0 Hz Sine Sweep, 40 mph). The solid line starts at 0.10 Hz and has a value of .0054 g/deg. The trace remains relatively flat until 0.7 Hz where it starts to drop reaching 0.0048 at 0.9 Hz and 0.0042 at 1 Hz. The dashed line starts at 0.0058 g/deg at 0.1 Hz. It rises only slightly to 0.006 at 0.2 Hz and then starts to descend slowly reaching 0.55 at 0.4 Hz, 0.5 at 0.6 Hz, and 0.45 at 0.9 Hz. This trace then remains relatively flat until 1 Hz.

Figure 10.29: Comparison of 40 mph, 0.1 to 1.0 and 0.1 to 2.5 Hertz Sinusoidal Sweep Frequency Response Curves – Roll Angle

This figure has two sub-plots or "panes". The x-axis is "Frequency in Hertz" from 0.01 Hz to 10 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axes are labeled Magnitude and Phase Angle from top to bottom. The Magnitude scale has units of degree/degree and ranges from 0 to 0.012. The Phase Angle scale has units of degrees and ranges from –100 to 200 degrees. These figures are only discussed for the range 0.1 to 1 Hz since this is overlap in the frequency range for the two test procedures.

The Phase Angle pane has two traces: one solid line that represents Test 120 (0.1 to 2.5 Hz Sine Sweep, 40 mph) and one dashed line that represents Test 125 (0.1 to 1.0 Hz Sine Sweep, 40 mph). The two traces are barely discernable from each other. Both traces begin at 0.12 Hz and have a value of -100 degrees. They then increase increasing sharply to 160 degrees at 0.2 Hz. Both traces then begin a descent (more gradual at first) to 100 degrees at 1.0 Hz.

The Magnitude pane has two traces: one solid line that represents Test 120 (0.1 to 2.5 Hz Sine Sweep, 40 mph) and one dashed line that represents Test 125 (0.1 to 1.0 Hz Sine Sweep, 40 mph). Both traces are very flat and vary between 0.045 and 0.049 degrees/degree for the range 0.1 to 1 Hz. The dashed line is slightly above the solid line from 0.1 to 0.5 Hz and slightly below it from 0.5 to 1 Hz.

Figure 10.30: Comparison of 40 mph, 0.1 to 1.0 and 0.1 to 2.5 Hertz Sinusoidal Sweep Frequency Response Curves – Roll Angle

This figure has two sub-plots or "panes". The x-axis is "Frequency in Hertz" from 0.01 Hz to 10 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axes are labeled Magnitude and Phase Angle from top to bottom. The Magnitude scale has units of degree/second/degree and ranges from 0 to 0.7. The Phase Angle scale has units of degrees and ranges from –300 to 0 degrees. These figures are only discussed for the range 0.1 to 1 Hz since this is overlap in the frequency range for the two test procedures.

The Phase Angle pane has two traces: one solid line that represents Test 120 (0.1 to 2.5 Hz Sine Sweep, 40 mph) and one dashed line that represents Test 125 (0.1 to 1.0 Hz Sine Sweep, 40 mph). The solid line starts at 0.10 Hz and a value of -55 degrees. The trace slowly ramps down to –100 degrees at 0.2 Hz, -150 degrees at 0.7 Hz, and –175 at 1 Hz. The dashed line begins at 0.1 Hz at –250 degrees and rises rapidly to –90 degrees at 0.2 Hz. The line then ramps down slightly above the solid line at first, but then merging with it at 0.5 Hz and above.

The Magnitude pane has two traces: one solid line that represents Test 120 (0.1 to 2.5 Hz Sine Sweep, 40 mph) and one dashed line that represents Test 125 (0.1 to 1.0 Hz Sine Sweep, 40 mph). The solid line starts at 0.10 Hz and has a value of 0.04 degree/second/degree. The trace then rises to 0.1 at 0.4 Hz, 0.21 at 0.7 Hz, and 0.25 at 1 Hz. The dashed line starts at 0.1 degree/second/degree at 0.1 Hz and slowly decreases to 0.08 at 0.2 Hz where it then slowly rises and merges with the solid line by 0.4 Hz. It then falls slightly below the solid line from 0.6 to 1 Hz.

Figure 10.31: Comparison of 40 mph, 0.1 to 1.0 and 0.1 to 2.5 Hertz Sinusoidal Sweep Frequency Response Curves – Yaw Rate

This figure has two sub-plots or "panes". The x-axis is "Frequency in Hertz" from 0.01 Hz to 10 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axes are labeled Magnitude and Phase Angle from top to bottom. The Magnitude scale has units of degree/second/degree and ranges from 0 to 0.45. The Phase Angle scale has units of degrees and ranges from –250 to 0 degrees. These figures are only discussed for the range 0.1 to 1 Hz since this is overlap in the frequency range for the two test procedures.

The Phase Angle pane has two traces: one solid line that represents Test 120 (0.1 to 2.5 Hz Sine Sweep, 40 mph) and one dashed line that represents Test 125 (0.1 to 1.0 Hz Sine Sweep, 40 mph). The solid line starts near 0.12 Hz and has a value of 0 degrees. The dashed line starts at 0.1 Hz and has a value of –10 degrees. These two trace merge at 0.2 Hz and –10 degrees and are barely discernable from each other from 0.2 to 1 Hz. The trace drop slowly from –10 degrees at 0.2 Hz to –25 degrees at 0.6 Hz, -40 degrees at 0.9 Hz, and –45 degrees at 1 Hz.

The Magnitude pane has two traces: one solid line that represents Test 120 (0.1 to 2.5 Hz Sine Sweep, 40 mph) and one dashed line that represents Test 125 (0.1 to 1.0 Hz Sine Sweep, 40 mph). The solid line starts at 0.10 Hz and has a value of .15 degree/second/degree. The trace remains relatively flat out to 1.0 Hz. The dashed line starts at 0.175 degree/second/degree at 0.1 Hz and then decreases slightly until it merges with the solid line at 0.2 Hz and 0.15 degree/second/degree. The dashed line is barely discernable from the solid line from 0.2 to 1 Hz.

Figure 10.32: Comparison of 0.2 Second Pulse Duration and Sinusoidal Sweep Frequency Response Curves – Corrected Lateral Acceleration

This figure has two sub-plots or "panes". The x-axis is "Frequency in Hertz" from 0.01 Hz to 10 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axes are labeled Magnitude and Phase Angle from top to bottom. The Magnitude scale has units of g/degree and ranges from 0 to 0.012. The Phase Angle scale has units of degrees and ranges from –400 to 0 degrees.

The Phase Angle pane has three traces: one solid line that represents Test 71 (Left Steer, 0.2 Second Pulse, 40 mph) one dashed line that represents Test 75 (Right Steer, 0.2 Second Pulse, 40 mph), and one dotted line that represents Test 120 (0.1 to 2.5 Hz Sine Sweep, 40 mph). These traces are very similar to each other. The dotted trace starts at 0 degrees and 0.1 Hz and merges with the solid and dashed traces that start at 0.2 Hz and -10 degrees. The traces then fall to -70 degrees by 1.0 Hz. They then fall more rapidly to –300 degrees at 2 Hz and –400 degrees at 4 Hz.

The Magnitude pane also has three traces: one solid line that represents Test 71 (Left Steer, 0.2 Second Pulse, 40 mph) one dashed line that represents Test 75 (Right Steer, 0.2 Second Pulse, 40 mph), and one dotted line that represents Test 120 (0.1 to 2.5 Hz Sine Sweep, 40 mph). The solid line starts at 0.2 Hz and has a value of 5×10^{-3} g/degree. The trace remains relatively flat until 0.8 Hz. It then decreases to 0.4×10^{-3} g/degree at 1.8 Hz and then rises to 4×10^{-3} g/degree and 4.0 Hz. The dashed line has a similar shape, but starts at a higher level (5.8×10^{-3} g/degree). This trace merges with the solid line near 1.3 seconds. The dotted line lies between the solid and dashed lines from 0.2 to 0.9 Hz. It then merges with the solid line at 1 Hz and is barely discernable from it at frequencies above this level.

Figure 10.33: Comparison of 0.2 Second Pulse Duration and Sinusoidal Sweep Frequency Response Curves – Roll Angle

This figure has two sub-plots or "panes". The x-axis is "Frequency in Hertz" from 0.01 Hz to 10 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axes are labeled Magnitude and Phase Angle from top to bottom. The Magnitude scale has units of degree/degree and ranges from 0 to 0.10. The Phase Angle scale has units of degrees and ranges from –50 to 200 degrees.

The Phase Angle pane has three traces: one solid line that represents Test 71 (Left Steer, 0.2 Second Pulse, 40 mph) one dashed line that represents Test 75 (Right Steer, 0.2 Second Pulse, 40 mph), and one dotted line that represents Test 120 (0.1 to 2.5 Hz Sine Sweep, 40 mph). These three traces have a very similar shape. The solid line starts at 0.2 Hz and 170 degrees. This trace slowly ramps down to 35 degrees at 1.8 Hz then rises to a small peak at 60 degrees at 2 Hz where it then drops to –30 degrees at 4 Hz. The dashed line has the same basic shape and begins 10 degrees below the solid line and becomes indiscernible from the solid line from 1.0 to 1.8 Hz. This trace reaches a higher peak (70 degrees) at the 2 Hz point, but is again barely discernable from the solid line beyond 2.4 Hz. The dotted line starts at 0.4 Hz and –50 degrees and rises to 165 degrees at 0.2 Hz. This trace follows the solid line very closely above 0.2 Hz.

The Magnitude pane also has three traces: one solid line that represents Test 71 (Left Steer, 0.2 Second Pulse, 40 mph) one dashed line that represents Test 75 (Right Steer, 0.2 Second Pulse, 40 mph), and one dotted line that represents Test 120 (0.1 to 2.5 Hz Sine Sweep, 40 mph). These three traces have the same basic shape. The solid line starts at 0.20 Hz and has a value of 0.041 degree/degree. This trace rises slightly to 0.042 at 0.8 Hz. It then ramps down to 0.012 degree/degree at 1.8 Hz. It then rises to a small peak of 0.018 at 2.7 Hz before falling to 0.008 at 4.0 Hz. The dashed line has the same basic shape but begins 0.01 degree/degree above the solid line (0.051 deg/deg). This dashed line also begins to fall at 0.8 Hz and the two lines are barely discernible beyond 1.8 Hz. The dotted line starts at 0.1 Hz and 0.041 degree/degree. From 0.2 to 1 Hz, the dotted line is slightly above the solid line, and above 1 Hz it is slightly below it.

Figure 10.34: Comparison of 0.2 Second Pulse Duration and Sinusoidal Sweep Frequency Response Curves – Roll Angle

This figure has two sub-plots or "panes". The x-axis is "Frequency in Hertz" from 0.01 Hz to 10 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axes are labeled Magnitude and Phase Angle from top to bottom. The Magnitude scale has units of deg/sec/degree and ranges from 0 to 0.60. The Phase Angle scale has units of degrees and ranges from –400 to 0 degrees.

The Phase Angle pane has three traces: one solid line that represents Test 71 (Left Steer, 0.2 Second Pulse, 40 mph) one dashed line that represents Test 75 (Right Steer, 0.2 Second Pulse, 40 mph), and one dotted line that represents Test 120 (0.1 to 2.5 Hz Sine Sweep, 40 mph). All three traces have the same basic shape and become barely discernible beyond 0.6 Hz. The solid line starts at 0.2 Hz and has a value of -105 degrees. The trace slowly ramps down to -240 degrees at 1.7 Hz then rises to -215 degrees at 2 Hz. The trace then decreases to –330 degrees at 4 Hz. The dashed line starts approximately 10 degrees below the solid line, but is barely discernible from the solid line by 0.6 Hz. The dotted line starts at –60 degrees at 0.1 Hz and drops to –100 degrees at 0.2 Hz. It then follows closely the path for the solid line.

The Magnitude pane also has three traces: one solid line that represents Test 71 (Left Steer, 0.2 Second Pulse, 40 mph) one dashed line that represents Test 75 (Right Steer, 0.2 Second Pulse, 40 mph), and one dotted line that represents Test 120 (0.1 to 2.5 Hz Sine Sweep, 40 mph). These three traces have the same basic shape. The solid line starts at 0.2 Hz and has a value of 0.05 degree/second/degree. The trace increases to 0.26 at 1.3 Hz and then falls to 0.13 at 1.8 Hz. The trace then rises to a second peak of 0.28 at 2.8 Hz and then falls to 0.23 at 4 Hz. The dashed line starts at 0.06, rises to 0.275 at 1 Hz, drops to 0.13 at 1.8 Hz and is then barely discernable from the solid line beyond this point. The dotted line starts at 0.03 degree/second/degree at 1 Hz and rises to 0.05 at 0.2 Hz, 0.1 at 4 Hz, 0.21 at 0.7 Hz, and 0.25 at 1 Hz. The trace then starts to decrease and reaches a trough of 0.1 degree/second/degree at 1.8 Hz. It then reaches a peak of 0.27 at 2.5 Hz.

Figure 10.35: Comparison of 0.2 Second Pulse Duration and Sinusoidal Sweep Frequency Response Curves – Yaw Rate

This figure has two sub-plots or "panes". The x-axis is "Frequency in Hertz" from 0.01 Hz to 10 Hz in logarithmic scale, with a factor of 10 at each increasing increment. The y-axes are labeled Magnitude and Phase Angle from top to bottom. The Magnitude scale has units of deg/sec/degree and ranges from 0 to 0.40. The Phase Angle scale has units of degrees and ranges from –200 to 0 degrees.

The Phase Angle pane has three traces: one solid line that represents Test 71 (Left Steer, 0.2 Second Pulse, 40 mph) one dashed line that represents Test 75 (Right Steer, 0.2 Second Pulse, 40 mph), and one dotted line that represents Test 120 (0.1 to 2.5 Hz Sine Sweep, 40 mph). All three traces have a very similar shape. The solid and dashed lines start at 0.2 Hz and -10 degrees, while the dotted line starts at 0.13 Hz and 0 degrees. The dotted line reaches –10 degrees by 0.2 Hz. All three traces then slowly decrease to -40 degrees at 1.0 Hz then more rapidly to -170 degrees at 4 Hz.

The Magnitude pane also has three traces: one solid line that represents Test 71 (Left Steer, 0.2 Second Pulse, 40 mph) one dashed line that represents Test 75 (Right Steer, 0.2 Second Pulse, 40 mph), and one dotted line that represents Test 120 (0.1 to 2.5 Hz Sine Sweep, 40 mph). All three traces have a similar shape. The solid line, Test 71, starts at 0.2 Hz and has a value of 0.14 degree/second/degree. The trace remains relatively flat until 0.6 Hz where it then starts to rise reaching a peak of 0.175 at 1.5 Hz and then drops to 0.06 at 4.0 Hz. The dashed line has the same basic shape but begins approximately 0.03 degree/second/degree above the solid line at 0.2 Hz and becomes barely discernible from the solid line by 1.8 Hz. The dotted line starts at 0.14 degree/second/degree at 0.1 Hz. By 0.2 Hz, the dotted line falls between the dashed and solid line. From 0.8 to 1.7 Hz, the dotted line lies slightly below the solid line. Above this level, it is barely discernable from the other two lines.

Figure 10.36 – Handwheel Angle as a function of Time for a Nominal Resonance Steer Test

This figure presents the shape of the handwheel input for a resonance steer test. The y-axis is labeled Handwheel Angle in degrees and ranges from -100 to +100 degrees in 20-degree increments. The x-axis is labeled Time in seconds and ranges from 0 to 18 seconds in 2-second increments.

The handwheel input is a constant 0.6 Hz frequency sine wave. The amplitude of the sine wave is 80 degrees. There are a 7 full cycles that start just prior to the 4 second mark and end at approximately 15.5 seconds.

Figure 10.37 – Corrected Lateral Acceleration as a function of Time for a Nominal Resonance Steer Test

This figure presents the shape of the Corrected Lateral Acceleration response for a resonance steer test. The y-axis is labeled Corrected Lateral Acceleration in g and ranges from –0.8 to +0.6 g in 0.2-g increments. The x-axis is labeled Time in seconds and ranges from 0 to 18 seconds in 2-second increments.

The Corrected Lateral Acceleration response to the sine wave handwheel input presented in Figure 10.36 is basically a sinusoid at the same frequency as the handwheel input. The amplitude of the sinusoid is approximately 0.52 to 0.58 g. There are 7 cycles of the sinusoid.

Figure 10.38 – Roll Angle as a function of Time for a Nominal Resonance Steer Test

This figure presents the shape of the Roll Angle response for a resonance steer test. The y-axis is labeled Roll Angle in degrees and ranges from –6 to +6 degrees in 2-degree increments. The x-axis is labeled Time in seconds and ranges from 0 to 18 seconds in 2-second increments.

The Roll Angle response to the sine wave handwheel input presented in Figure 10.36 has a basic sinusoid shape at the same frequency as the handwheel input. The peaks on the sinusoid are more pointed than a true sine wave. The amplitude of the sinusoidal peaks has a range of approximately 5 to 5.5 degrees. There are 7 cycles of the sinusoid.

Figure 10.39 – Roll Rate as a function of Time for a Nominal Resonance Steer Test

This figure presents the shape of the Roll Rate response for a resonance steer test. The y-axis is labeled Roll Rate in degrees/second and ranges from –30 to +30 degrees/second in 10-degree/second increments. The x-axis is labeled Time in seconds and ranges from 0 to 18 seconds in 2-second increments.

The Roll Rate response to the sine wave handwheel input presented in Figure 10.36 is not nearly as smooth as the previously presented Lateral Acceleration and Roll Angle responses. The amplitude of the peaks is approximately 22 to 25 degrees/second and there are 7 cycles.

Figure 10.40 – Yaw Rate as a function of Time for a Nominal Resonance Steer Test

This figure presents the shape of the Yaw Rate response for a resonance steer test. The y-axis is labeled Yaw Rate in degrees/second and ranges from –20 to +20 degrees/second in 5-degree/second increments. The x-axis is labeled as Time in seconds and ranges from 0 to 18 seconds in 2-second increments.

The Yaw Rate response to the sine wave handwheel input presented in Figure 10.36 has a basic sinusoid shape. The amplitude of the sinusoidal peaks is approximately 15 to 17 degrees/second. There are 7 cycles of the sinusoid.

Figure 10.41 – Corrected Lateral Acceleration Frequency Response Using "Resonance" Steering Profile – 40 mph

The y-axis is labeled Magnitude and has units of g/degree. The y-axis range is from 0 to 0.006 g/degree in 0.001-g/degree increments. The x-axis is Frequency in Hertz ranging from 0.6 to 1 Hertz.

This figure contains three traces labeled 80, 100, and 120 degrees. The Corrected Lateral Acceleration magnitude frequency response for the 80-degree steering input starts at 0.0053 g/degree and falls only slightly to 0.0052 at 0.7 Hz, 0.0049 at 0.8 Hz, 0.0047 at 0.9 Hz and 0.0044 at 1 Hz. The 100 and 120 degree steering inputs are very similar beginning at 0.005 g/deg at 0.6 Hz, 0.0047 at 0.7 Hz, 0.0044 at 0.8 Hz, 0.004 at 0.9 Hz and 0.0035 at 1 Hz (the 120 degree values actually stop at 0.9 Hz).

Figure 10.42 – Roll Angle Frequency Response Using "Resonance" Steering Profile – 40 mph

The y-axis is labeled Magnitude and has units of degree/degree. The y-axis range is from 0 to 0.06 degree/degree in 0.01 degree/degree increments. The x-axis is Frequency in Hertz ranging from 0.6 to 1 Hertz.

This figure contains three traces labeled 80, 100, and 120 degrees. The Roll Angle magnitude frequency response for the 80-degree steering input starts at 0.05 degree/degree and increases only slightly to 0.051 at 0.7 Hz before dropping slightly to 0.049 at 0.8 Hz and remains flat out to 1 Hz. The 100-degree input begins at 0.05 degree/degree at 0.6 Hz, falls to 0.047 at 0.7 Hz and remains flat to 0.8 Hz, then falls slightly to 0.044 at 0.9 Hz where the data ends. The 120-degree steering input begins at 0.045 degree/degree at 0.6 Hz, rises to 0.047 at 0.7 Hz and remains relatively flat to 0.8 Hz, then drops to 0.042 at 0.9 Hz and 0.040 at 1 Hz.

Figure 10.43 – Roll Rate Frequency Response Using "Resonance" Steering Profile – 40 mph

The y-axis is labeled Magnitude and has units of degree/second/degree. The y-axis range is from 0 to 0.3 degree/second/degree in 0.05-degree/second/degree increments. The x-axis is Frequency in Hertz ranging from 0.6 to 1 Hertz.

This figure contains three traces labeled 80, 100, and 120 degrees. The Roll Rate magnitude frequency response for the 80-degree steering input starts at 0.19 degree/second/degree at 0.6 Hz, rises to 0.225 at 0.7 Hz, then to 0.24 at 0.8 Hz, up to 0.27 at 0.9 Hz, and finally up to 0.29 at 1 Hz. The 100-degree steering input begins at 0.23 and remains flat until 0.7 Hz, where it starts to rise reaching 0.25 at 0.8 Hz, and 0.275 at .9 Hz where the trace ends. The 120-degree steering input begins at 0.23 at 0.6 Hz remains flat until 0.7 Hz where it starts to lower reaching 0.22 at 0.8 Hz, and then rising to 0.23 at 0.9 Hz and 0.24 at 1 Hz.

Figure 10.44 – Yaw Rate Frequency Response Using "Resonance" Steering Profile – 40 mph

The y-axis is labeled Magnitude and has units of degree/second/degree. The y-axis range is from 0 to 0.3 degree/second/degree in 0.05-degree/second/degree increments. The x-axis is Frequency in Hertz ranging from 0.6 to 1 Hertz.

This figure contains three traces labeled 80, 100, and 120 degrees. The Yaw Rate magnitude frequency response for the 80-degree steering input starts at 0.16 degree/second/degree at 0.6 Hz, rises to 0.17 at 0.7 Hz, remains flat to 0.8 Hz, and then rise to 0.175 at 0.9 Hz, and 0.18 at 1 Hz. The 100-degree steering input begins at 0.17 degree/second/degree and remains at this level until 0.7 Hz, then rises slightly 0.18 at 0.8 Hz, and 0.19 at .9 Hz where the trace ends. The 120-degree steering input begins at 0.165 degree/second/degree and rises to 0.175 at 0.7 Hz, 0.18 at 0.8 Hz, 0.19 at .9 Hz, and 0.195 at 1 Hz.

Figure: 11.1: Pulse Steer Handwheel Input

This figure represents the shape of the pulse steer handwheel input. The y-axis is labeled Handwheel Angle and the x-axis is labeled Time.

The handwheel angle trace is a triangle. The handwheel angle starts at 0 degrees, increases to 80 degrees in 0.1 seconds and decreases back to 0 in another 0.1 seconds. In other words, the triangle has a base equal to 0.2 seconds and a height of 80 degrees.

Figure 11.2: Handwheel Steering Input for the Sinusoidal Sweep Maneuver.

This figure represents the shape of the handwheel input for the Sinusoidal Sweep maneuver. The y-axis is labeled Handwheel Angle in degrees and ranges from -100 to +100 degrees in 20-degree increments. The x-axis is labeled Time in seconds and ranges from 0 to 25 seconds in 5-second increments.

As the maneuver name implies, the handwheel input is a swept sine that starts at a low frequency (longer duration), increases to a high frequency (shorter duration), and then returns to a low frequency. The amplitude of the sinusoidal peaks is 80 degrees. There are a total of 15 negative peaks and 14 positive peaks.

Figure 11.3: Slowly Increasing Steer Test Handwheel Input

The x-axis is labeled Time from 0 to 20 seconds, and the y-axis is labeled Handwheel Angle. This figure shows the Slowly Increasing Steer to be a ramp function with the handwheel angle ramping up to 200 degrees over a 20 second period. The handwheel angle is then held constant at this level.

Figure 11.4: Slowly Increasing Speed Test Handwheel Input

The x-axis is labeled time and the y-axis is labeled handwheel angle. This figure shows that the Slowly Increasing Speed handwheel input is a very fast steering input to a level that produces 0.7 g lateral acceleration when the vehicle is traveling at 50 mph. This handwheel angle is then held constant for the duration of the test. While the handwheel angle is held constant, the vehicle speed is increased from 35 to 50 mph.

STILL NEED TO WORK ON
Figure 11.5: Comparison of Fishhook with Pulse Brake and J-Turn with Pulse Brake – Handwheel and Brake Pedal Inputs

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Handwheel Angle in degrees and Brake Pedal Force in pounds-force. The top pane has a range of –400 to 400 degrees in 200-degree increments and the bottom pane has a range of -100 to 200 pounds-force in 50-pounds-force increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 6 seconds in 1-second increments.

The upper pane has two traces that represent the measured Handwheel Angle for Test 295, which was a J-Turn test, and Test 235, which was a Fishhook test. The dashed line, Test 235 Fishhook, starts at the origin and remains level until 0.3 seconds where it starts to rise reaching a peak at 0.8 seconds and 280 degrees. This trace then reverses direction and reaches –350 degrees at 2.3 seconds. It remains near this level until 4 seconds where it begins to rise with some minor oscillations. The trace ends at 6 seconds and –250 degrees. The solid line for test 295 (J-Turn) begins at 1.2 seconds and 0 degrees and falls abruptly to –330 degrees at 1.8 seconds. The trace remains at this level out to 6 seconds. This trace does not begin at the origin because the time histories for these two tests were aligned based on brake pulse peak magnitude.

The lower pane also has two traces that represent the Brake Pedal Force for Tests 295 and 235. Both traces begin with zero magnitude and remain flat until the brake application is made. They return to zero and stay flat after the brake application. The brake application for Test 295 starts at 2.4 seconds and is 0.55 second in duration. The apex is located near 2.75 seconds and has a 165 pounds-force magnitude. The brake application for Test 336 begins near 2.5 seconds and is 0.4 seconds in duration. The apex is located near 2.75 seconds (in line with the apex for Test 295) and has a 150 pounds-force magnitude.

Figure 11.6: Comparison of Fishhook with Pulse Brake and J-Turn with Pulse Brake Results - Corrected Lateral Acceleration and Roll Angle Vehicle Responses

This figure contains 2 subplots or "panes". The top and bottom pane y-axis labels are, respectively, Corrected Lateral Acceleration in g and Roll Angle in degrees. The top pane has a range of –1.5 to +1 g in 0.5-g increments and the bottom pane has a range of -10 to +15 degrees in 5-degree increments. The x-axis is labeled Time in seconds (for both figures) and has a range of 0 to 6 seconds in 1 second increments.

The upper pane has two traces that represent the Corrected Lateral Acceleration for Tests 295 (J-Turn) and 235 (Fishhook). Test 235, indicated by a dashed line, starts near the origin and remains flat until approximately 0.4 second. The trace then ascends to approximately +0.7 g at 1 second and stays near this level until 1.4 seconds. The trace then falls to –0.6 g at 2.3 seconds. This is followed by a rise due to the brake pulse application shown in Figure 11.5. The trace rises to –0.3 g at 2.85 seconds and then decreases to -0.75 g at 3.1 seconds. With some undulations, the trace rises slowly reach –0.2 g at 6 seconds. The solid line for test 295 does not begin until 1.2 s and 0 g and stays relatively flat for approximately 0.2 seconds before it begins to drop to –0.65 g at 1.8 seconds. It stays relatively flat at this level until 2.1 seconds where it again lowers to –0.75 g at 2.3 seconds. The trace then rises rather abruptly due to the brake pulse application shown in Figure 11.5. It reaches a peak of –0.2 g at 2.9 seconds before reversing direction and reaching a negative peak of –0.8 g at 3 seconds. This trace goes through one more oscillation and then settles out to –0.6 g at 4 seconds. The trace remains near this level for the duration of the time history.

The lower pane also has two traces that represent the Roll Angle for Tests 295 and 235. Test 235, indicated by a dashed line, starts near the origin and remains flat until approximately 0.5 second. The trace then descends to approximately –5 deg at 0.8 second. The trace then rises to a peak of 7 degrees at 2.2s and 7 deg at 2.3 seconds. The trace then decreases due to the brake pulse application reaching a low of 3 degrees at 2.9 seconds. This is followed by another peak of 13.5 degrees at 4 seconds. The line then falls to 3 degrees at 4.7 seconds and remains fairly flat until the end of the time history. The solid line for Test 295 and a J-Turn begins at 1.2 seconds and 0 degrees and remains relatively flat until 1.5 seconds where it starts to rise reaching a peak of 6 degrees at 1.9 seconds. The line then has a minor dip and again rises to 6 degrees at 2.5 seconds. The line then has a much larger dip due to the brake pulse application reaching a low of 0 degrees at 2.9 seconds followed by a peak of 12 degrees at 3.3 seconds. The line then drops to 5 degrees where it remains until the end of the time history.

Figure 11.7: J-Turn and J-Turn with Pulse Brake Handwheel Input

The x-axis is labeled Time and the y-axis labeled Handwheel Angle. Starting at time 0 the steering controller sharply turns the handwheel to 330 degrees in 0.33 seconds (1000 degree/second rate). The handwheel is then held constant at 330 degrees for the duration of the test.

Figure 11.8: J-Turn with Pulse Braking – Pulse Shape

The x-axis is labeled Time and the y-axis is labeled Brake Pedal Force. This figure shows the basic brake pedal pulse shape, which is a short duration pulse that has a 200 pounds-force magnitude. This pulse is applied 1 second after the 330 degrees handwheel input has been reached.

Figure 11.9: Fishhook #1 Handwheel Input

The x-axis is labeled Time and the y-axis is labeled Handwheel Angle. The initial steer angle is negative and reaches –270 degrees where it remains for a short period of time before reversing direction to +600 degrees where it is held constant for the duration of the test. At the base of the figure it states that the “Steering Rates are Based on the Roll Natural Frequency”.

Figure 11.10: Fishhook #2 Handwheel Input

The x-axis is labeled Time and the y-axis is labeled Handwheel Angle. The initial steer angle is negative and reaches –7.5 times the handwheel-to-road-wheel ratio. It remains at this level for a short period of time before reversing direction to +600 degrees where it is held constant for the duration of the test. At the base of the figure it states that the “Steering Rates = 500 degree/second”.

Figure 11.11: Comparison of Handwheel Angle Steering Inputs for the Fishhook 1 and Fishhook 2 Maneuvers

The x-axis is labeled Time and has a range of 0 to 10 seconds in whole second increments. The y-axis is labeled Handwheel Angle in degrees with a range of –700 to +300 degrees in 100-degree increments. There are two traces: Fishhook 1 and Fishhook 2. Both traces are flat until approximately 3.25 seconds. The Fishhook 1 trace (thin solid line) then ramps up to 270 degrees reaching this value near 3.7 seconds.

It then remains at this level until approximately 3.95 seconds where it ramps down to –600 degrees near 5 seconds. It then remains at this level until approximately 8 seconds before reversing direction and heading back to the x-axis. The Fishhook 2 trace (thick solid line) ramps up to140 degrees reaching this value near 3.6 seconds. It then remains at this level until slightly after 4 seconds. It then reverses direction to –600 degrees at 5.6 seconds where it remains flat until 8.5 seconds where it starts to return towards the x-axis.

Figure 11.12: Handwheel Steering Input for the Resonant Steer Maneuver

This figure represents the shape of the handwheel input for the Resonant Steer maneuver. The y-axis is labeled Handwheel Angle in degrees and ranges from -150 to +150 degrees in 50-degree increments. The x-axis is labeled Time in seconds and ranges from 0 to 25 seconds in 5 second increments.

The handwheel input is a constant 0.5 Hz frequency sine wave. The amplitude of the sine wave is 110 degrees. There are a 10 full cycles that start near the 4 second mark and end at approximately 24 seconds.